Power Take-off System Design for Wing-Wave WEC

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We the undersigned committee hereby recommends that
the attached document be accepted as fulfilling in part the requirements for the degree of
Master of Science in Ocean Engineering

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Abstract

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The oceans represent a massive untapped energy resource with potentially more energy than the aggregated output of all other resources on the earth. In recent years, there has been a growing focus globally on the development of economical and efficient conversion technologies for the ocean energy.

The work in this thesis presents a system for power conversion and extraction, truning the ocean's waves energy into electrical energy. The main goal of the study was to design, and develop a Power Take-off system for the 'Wing-Wave', a flap-type sea-bed mounted wave energy converter (WEC). The power take-off system consisted of hydraulic, electrical and control subsystems to evaluate the performance of Wing-Wave. The wave energy was captured in form of hydro-mechanical energy by the pistons coupled with the flap of Wing-Wave. This hydraulic energy was then converted to electrical energy by an impulse-type turbine. The control system was designed with wireless data acquisition capability for the remote viewing and control.

Full scale prototypes of the power take-off system were deployed and tested using the Wing-Wave in the summer of 2012 and 2013. The prototypes successfully demonstrate the wave energy capture in the deployment.

Index Terms— Ocean Energy, Wave Energy, Wave Energy Convertors, Wireless, Power take-off, Renewable energy

"I am a citizen of the most beautiful nation on earth,
a nation whose laws are harsh yet simple,
a nation that never cheats,
which is immense and without borders,
where life is lived in the present.

In this limitless nation, this nation of wind, light, and peace,
there is no other ruler besides the sea."

--Bernard Moitessier

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List of Symbols

Constants

π	3.141 592 654
e	2.718 281 828
g	9.81 m/s^2

Variables

a	Amplitude of wave	[m]
B_f	Width of Flap	[m]
C_D	Drag coefficient	[-]
C_M	Inertia coefficient	[-]
f	frequency	[Hz]
g	gravity	[m/s^2]
h	Depth	[m]
h_1	Distance between top of flap and surface	[m]
h_f	Height of Flap	[m]
h_p	Height of Piston Connection	[m]
H	Wave Height	[m]
k	Wave Number	[m^{-1}]
L	Wavelength	[m]
L_f	Stroke length	[m]
M_f	Mass of Flap	[kg]
V_f	Flap Volume	[m^3]
t_f	Flap Thickness	[m]
T	TimePeriod	[s]
ρ_f	Flap density	[kg/m^3]
ρ	Density	[kg/m^3]
ω	Angular Frequency	[rad]
ν	Kinematic Viscosity	[m^2/s]

Acronyms

ADC	Analog digital converter
ARM	ARM (formerly Advanced RISC Machine)
FIT	Florida Institute of Technology
WEC	Wave Energy Convertor
RTC	Real Time Clock
LPM	Liter per Minute (Flow)
I/O	Input and Output

Dedication

To my Ammi and Abbu

All that I have achieved yet in my life and
will ever achieve in coming days,
I owe to them.

Preface

"You can put a teddy bear out in waves, and it will absorb energy."

-Brian Count (Scher, 1985)

This thesis is part of my effort to understand the energy behind the bobbing teddy bear in the waves. The time period was short but the experience and the learning are going to stay with me for much longer time.

I humbly consider myself very fortunate to have support of so many people in my personal and academic life for the completion of my Masters. First of all, I would like to express my gratitude to Fulbright Program and U.S. Department of State for giving me an opportunity to come to US and complete my Masters.

Then I am extremely thankful to my advisor, Dr. Stephen Wood, for all his support, patience and and supervision during my study. I am also grateful to my thesis committee members, Dr. George Maul and Dr. Hector Gutierrez for their guidance and valueable suggestions.

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I would also like to acknowledge the generous help by Mr. Lee Marcum (SebaiCMET, Inc, Clean and Green Enterprises, Inc) and Mr. S Ibne Hasan (Intech Automation). I am also thankful to Mr. Bill Battin for his help on very short notices.

I had honor of working with two undergraduate student teams during this thesis and I am very grateful for their tremendous effort throughout the construction and deployment of the Wing-Wave. For 2012: Billy, Patrick, Sitara, Mario, Chad and Alexej; For 2013: Tolu, Abbie, Jacob, Hallana, Kevin and Marine.

Also I am greatly indebted to my grad lab fellows, Matthew Jordan and Anthony, Jones for their time, assistance and help.

In end, a very special thanks goes to the person without whose support and sacrifices it would not have been possible for me to get this done: my better half, Madiha. She was not present physcially with me during this time but it was her support that kept me going through some real tense parts of my study.

Ismail Sultan
July 28, 2013

Part I

Problem Introduction and Background

Chapter 1

Introduction

Throughout the history, the oceans have greatly influenced the way mankind has survived and evolved. The climate and the weather system, on which the human race depends for its survival, is a result of the interaction between the ocean and the atmosphere. The ocean cover more than three quarters of Earth (Nybakken and Webster 1998). As of today, over half of the world population lives less than 200 kilometers away from the oceans (Hinrichsen 1999).

The enormous size of the oceanic bodies and processes may have the hidden answer to the energy appetite of the world. Maybe the 'blue' solution is the sustainable, environment friendly and reliable solution our future generations would need.

This is the domain in which this work attempts to contribute. The following parts of this chapter will present the motives for the present study, as well as, a statement of the problem to be addressed

1.1 Motivation

Depletion of fossil fuel reserves and environmental disasters have changed the global attitude toward energy issues. A major future energy crisis is seen only as a matter of time if the dependency on fossil fuels as main source of energy doesn't change soon. The exponential growth in human population and resulting high energy demands may deplete the currently known fossil fuel reserves in 40 years (Shafiee and Topal 2009). The awareness of this danger has resulted in a significant shift of energy research towards renewable energy resources.

One of the major renewable energy resources, in addition to wind and solar, is ocean energy. The oceans cover almost 360 million square kilometers i.e. approximately 72% of the Earth (Nybakken and Webster 1998). They represent an enormous untapped energy resource containing potentially more energy than the aggregated output of all other resources on the earth. It is estimated that the theoretical potential of the ocean related energies is up to 2 Million Terawatt-hours (UNDP 2000).

Ocean energy is actually a derived form of solar energy and result of complex wind-wave interactions (Knauss 2005). Ocean Energy is stored partly in the form of kinetic energy from the motion of waves and currents and partly as thermal energy from the sun. Different forms of Ocean energy are thermal, salinity, currents, tidal and wave. Out of these forms, wave and tidal have been in the limelight of R&D efforts because of the abundance and broad access (Bard and Schmid 2005). Compared to other renewables resources, wave energy has a higher energy density, a higher availability and better predictability (Brekken and Han 2009). Figure 1-1 shows world map with the potential wave power as kW/m of the wave front.

Despite the enormous potential of ocean energy, there are some major obstacles due to which the development of ocean energy technology lags when compared to those for solar and wind. The challenges include the inherent unstable and uncertain nature of ocean energies, accessibility and extreme weathers. These result in stringent engineering design requirements and eventually relatively higher costs for ocean energy research. Increasing

Figure 1-1: Annual average estimated global wave power in kW/m (Barstow and Kabuth 2010)

power quality demands for the power grid integration adds to the complexity of the problem. These issues also lengthen the design cycle time required for new technology development.

For the researchers working in the field of ocean energy, reliable, low-cost and effective evaluation of the ocean energy conversion technologies is critical for their successful and smooth integration into the large power systems. These tools are indispensable for concept verifications on a small-scale (e.g., research and development) and can assist in the rapid and successful transformation of ocean renewable energy technologies from prototype to full-scale matured systems.

1.2 Problem Statement

The Ocean Engineering Department at Florida Institute of Technology (FIT) is currently working on two prototypes of Wave Energy Convertors (WEC): Wing-Wave, a sea-bed mounted bottom hinged type WEC that captures energy from the horizontal component of wave orbitals at varying depths and GECCO, a surface floating attenuation WEC for harnessing surface waves.

Concept verification of these WEC's designs was done in 2010 and 2011. Sea-test scale models were developed and successfully deployed. However, no Power Take-Off (PTO) system was designed to capture the energy and convert it to electricity. Furthermore there was limited instrumentation on these WECs, which was not sufficient to understand the operational performance completely.

In 2012 and 2013, focus of the work on the Wing-Wave and GECCO was broadened to develop a basic Power Take-Off (PTO) for the evaluation of the electrical generating potential of the devices. Later in 2013, it was decided to focus on Wing-Wave only for

Figure 1-2: (Left) Wing-Wave WEC (Right) GECCO WEC

development to save efforts and time.

1.3 Scope and objectives

The main goal of this thesis is to evaluate the wave energy capture potential of the *Wing-Wave* through testing and real-sea deployment. To achieve this goal, following objectives were set:

1. Design and development of a complete 'Power Take-off' system for deployment with Wing-Wave. This would include:
    a. Hydraulics system
    b. Instrumentation and control valves
    c. Power system for the electrical load
    d. Control and data acquisition system (with wireless connectivity)
    e. Human Machine Interface Software for real-time viewing.
2. Ocean deployment of the PTO with Wing-Wave and real-time data acquisition.
3. Development of a mathematical framework for the Wing-Wave WEC, and Power Take-Off System (including the hydraulic systems).

Figure 1-3 shows the scope of this thesis. Work flow of the combined Wing-Wave and PTO system is as following: Wave energy is converted into hydro-mechanical energy by the pistons connected with the flap of Wing-Wave, which drives a Pelton/impulse turbine coupled with an alternator. The energy is then fed into the power module that regulates the electrical output. The control system controls the hardware, records instrumentation data, and sends data via the wireless connection. The user is able to monitor the real-time data through the Human Machine Interface (HMI) software and send commands remotely. The power take-off system is housed in a floating raft anchored at the surface near the wave energy converters during testing. Figure 1-4 shows the overall energy flow of the system

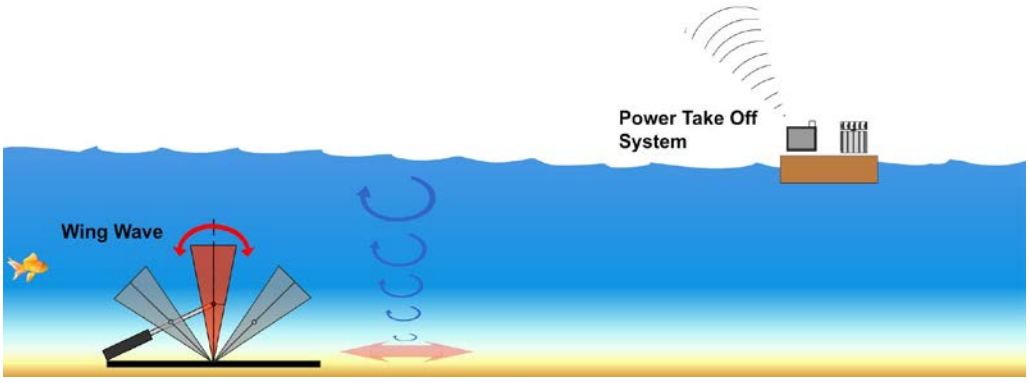


Figure 1-3: Thesis Scope (Wing-Wave WEC and PTO System)

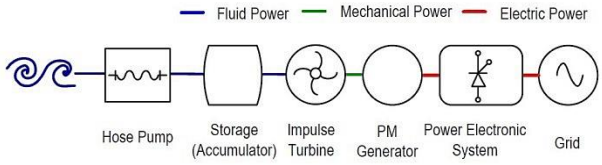


Figure 1-4: Basic Energy Flow Diagram for Wing-Wave WEC (Khan et al. 2008)

from wave-to-wire.

Note: The work in this thesis doesn't include any grid connectivity related issue due to limited time and resources.

1.4 Outline of the Thesis

This thesis is divided into 9 chapters. Chapter 1 gives an introduction of the problem and the goals set for this thesis.

In Chapter 2, an overview of important concept regarding the subject is presented which includes the ocean waves, control/embedded systems, hydraulics and power. Chapter 3 presents the project background. It covers the literature reviewed, and an overview of the work that has been done at Florida Institute of Technology on ocean energy.

Chapter 4 presents the hardware design for the system. Chapter 5 and 6 present the laboratory testing and deployment of the system. Discussion on the results and observations regarding deployment is included.

Chapter 7 presents the mathematical equations and framework needed to model a flap type WEC. The forces acting on the flap and PTO are calculated using different approaches.

The last section of this document is on the further work required for the Wing-Wave and the conclusion of the work done in this document.

Chapter 2

Theory

Before moving to the sections related to design and mathematical modeling of the system, some basic concepts and terminologies will be introduced in this section. The first section focuses on the concepts that are fundamental in understanding the mechanics behind the Wave Energy Convertor. This includes the fluid mechanics, waves and marine hydrodynamics.

The second part describes the technicalities of the Power Take-off system. An overview of the electrical, control and hydraulic systems is presented.

2.1 Fluid Mechanics

2.1.1 Bernoulli's Equation

Bernoulli's principle is actually a derived form of conservation of energy for fluid dynamics. It relates the potential and kinetic energy for an inviscid steady flow. It is given as (Munson, Young, and Okiishi 2002):

$$\frac{p_1}{\rho} + \frac{v_1^2}{2g} + z_1 = \frac{p_3}{\rho} + \frac{v_3^2}{2g} + z_3 + h_s - h_L \qquad 2\text{-}1$$

Where h_s and h_L represent the head shaft and head loss respectively. The Bernoulli's equation will be used for hydraulic system calculations.

2.1.2 Buoyancy

Buoyancy force is the upward force exerted by the fluid on a body immersed in it (Munson, Young, and Okiishi 2002).

$$B = \rho g V_{body} \qquad 2\text{-}2$$

If the buoyancy force and the weight of the immersed body are equal then the body would float in equilibrium. The body will sink if buoyancy is less and will rise if buoyancy is greater as compared to its weight.

2.1.3 Viscosity

Viscosity represents the resistance to flow offered by the fluid. Viscosity is due to inherent friction resulting from the shear stress between adjacent layers of the fluid that are moving at different velocities. A fluid with no resistance to shear stress is known as an inviscid fluid.

Dynamic viscosity is determined by the shear stress effect on the two adjacent layers of the fluid. *Kinematic viscosity* is the ratio between dynamic viscosity and fluid density.

2.1.4 Reynolds Number

Reynolds Number R_e is the measure of the ratio of inertial forces to the viscous forces in the fluid flow. It is helpful to determine the relative influence of these two forces on the flow. It is defined as a function of relative fluid velocity, dynamic viscosity of the fluid and characteristic distance. R_e number is used to determine the flow nature. Low Reynolds numbers indicates a smooth laminar flow whereas higher values of R_e show that flow would be turbulent and will have chaotic eddies and vortices. R_e number is determined as (Munson, Young, and Okiishi 2002)

$$R_e = \frac{uD}{\upsilon} \qquad 2\text{-}3$$

2.1.5 Drag

Drag forces are the resistive forces which act on the solid body in the direction of relative fluid velocity. Drag forces depend on the velocity and the shape of the body. It is given as (Munson, Young, and Okiishi 2002):

$$F_D = \frac{1}{2} C_D \rho A \, u \, |u| \qquad 2\text{-}4$$

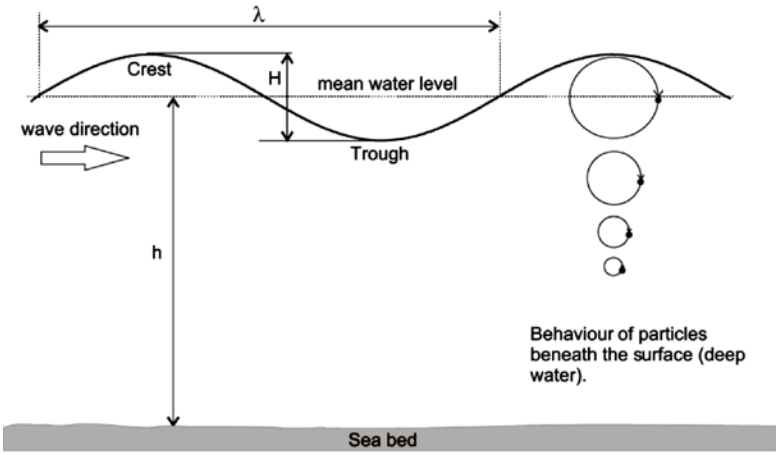


Figure 2-1: Wave Characteristics (Bostrom 2011)

2.2 Wave Basics

2.2.1 Wave characteristics

Waves are generally characterized by the following properties as shown in Figure 2-1 **(Hoen 2009)**:

1. Wave height H (from trough to crest)
2. Wavelength λ or L (from crest to crest)
3. Wave period T (time interval between arrival of consecutive crests at a stationary point)
4. Wave propagation direction
5. Depth h

All other properties, like velocity and acceleration are derived from these above.

WAVE TYPE	PERIOD	DISTURBING FORCE	RESTORING FORCE
Capillary	<0.1 sec	Wind	Surface tension
Ultra gravity	0.1-1 sec	Wind	Gravity
Gravity	1-30 sec	Wind	Gravity
Infra gravity	0.5-5 min	Wind	Gravity
Long Period	0.1-12 hr.	Storms/Earthquakes	Gravity/Coriollis
Tidal	12-25 hr.	Gravitation	Gravity/Coriolis
Trans-tidal	>1 day	Land-air-sea coupling	Gravity/Coriolis

Table 2-1: Ocean Wave Types (Knauss 2005)

Celerity or the speed of wave C is defined as L/T .

2.2.2 Creation of waves

The formation of ocean waves is the result of a meteorological interaction of ocean, wind and solar incident energy on earth (Knauss 2005). The uneven solar heating of the earth's surface drives the large scale wind systems. In turn this wind system initiates the wave formation in the ocean. The parameters that determine the magnitude of the waves formed are:

1. Wind speed
2. Wind Fetch (Distance on which the wind has blown over)
3. Width of area affected by fetch
4. Time duration the wind has blown over a given area

Wind blowing across the surface of the ocean over the fetch zone creates a tangential stress on the water surface, resulting in the initial formation of a wave. The pressure and shear stress variations at the surface of the water helps to build and propagate the wave. When these fluctuations are in phase with the existing wave oscillations, further wave propagation occurs. Once the waves are initiated due to wind interaction, waves do not require winds for further propagation. These wind generated waves are called free waves or swells. Depending on their wavelengths and travel distance, these waves eventually either dissipate during their travel or interact with a coastline.

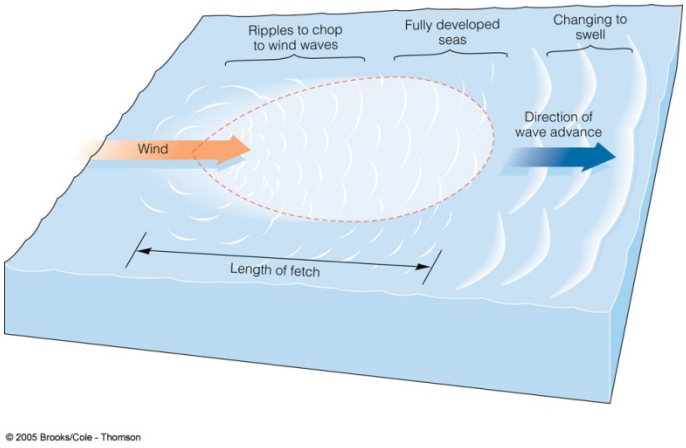


Figure 2-2: Wave formation in ocean[1]

[1]Web: <http://science.kennesaw.edu/~jdirnber/oceanography/LecturesOceanogr/LecWaves/LecWaves.html>

The research in this thesis uses the wind-waves with longer time periods, or swells. Table 2-1 shows typical wave types characterized by their period, disturbing and restoring forces.

2.2.3 Linear theory of ocean waves

Depending on the depth and height to length (H/L) ratio of the waves, two theories can be used for understanding wave behavior. For most waves in deep water, where H is much smaller than L, the linear wave theory or Airy theory can be used (Dean and Dalrymple 1991). For steep waves, where the H/L is significant, Stokes second order theory is used. For the discussion and mathematical calculations in this thesis, we will use linear theory of ocean waves.

Linear wave theory assumes that the amplitude of waves on the water surface is infinitely small as compared to surface dimensions. The flow is 2-dimensional and waves travel in the *x*-direction. The effect of Coriolis force and viscosity is negligible (Waters 2008).

The sea-surface elevation η of a wave traveling in the x direction can be represented as sinusoidal (Dean and Dalrymple 1991):

$$\eta(x,t) = a\,sin(k\,x - \omega t) \qquad \textbf{2-5}$$

where

$$\omega = \frac{2\pi}{T}; k = \frac{2\pi}{L} \qquad \textbf{2-6}$$

Here ω is wave frequency in radians per second and k is wave number. The detailed formulation of the problem would be done in the Chapter 7. For now, we will show the solution for a progressive monochromatic wave for linear theory which is:

$$\omega^2 = g\,k\,tanh\,(kh) \qquad 2\ 1$$

The equation above is also known as the dispersion relation.

2.2.4 Wave Shoaling

When waves propagate through the ocean, the energy is transferred in the direction of propagation. However, the water particle displacement is in circular orbits about their mean position. These movements are referred as *wave orbitals*. In the deep water, where $h \leq \frac{L}{2}$, these orbitals are circular with the diameter as exponentially decreasing function of the depth.

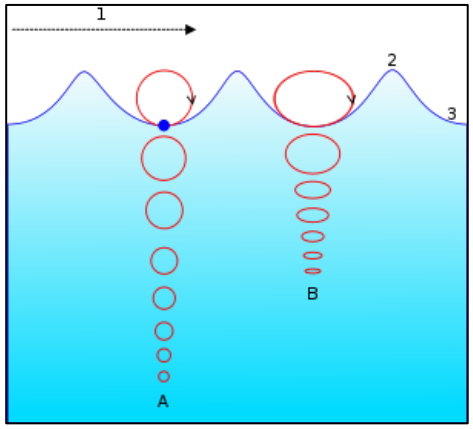


Figure 2-3: Wave Orbitals (Wikipedia 2013)

As shown in Figure 2-3, when waves from deep water (A) enter into the shallow water (B), these wave orbitals become from circular to elliptical. In near-to-shore regions, these orbitals flattens due to seabed friction and turn into almost a back and forth horizontal displacement, which amplifies the horizontal movement of the water particles. This horizontal movement is called the wave surge.

This phenomenon of depth dependency of the wave orbital movement is "Wave Shoaling". "Wave Shoaling" is the key principle on which surge-type wave energy convertors are designed.

2.2.5 Wave energy

The energy transported by the wave is mainly the function of the wave height only. It is given as (Dean and Dalrymple 1991):

$$E_T = \frac{1}{8}\rho g H^2 \qquad 2\text{-}7$$

The total energy per wave per width is given as:

$$E_T = \frac{1}{8}\rho g H^2 L \qquad 2\text{-}8$$

For deep water, 95% of the energy in the waves is available between the surface and a depth h = L/4 (Bostrom 2011).

2.3 Power Take-off

The conversion of captured hydro-mechanical energy to electrical energy, or 'Power Take-off' (PTO) mechanisms, depends on the working principle of the energy device and typically could be mechanical, hydraulic or a direct driven system (MuellerI and Baker 2005). Figure 2-4 compares different PTO schemes generally applied for ocean energy devices:

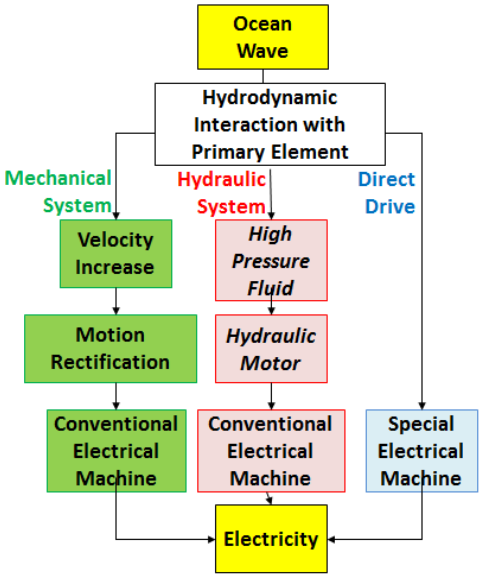


Figure 2-4: PTO types

In WEC, incoming power is generally oscillating at low frequency with high torque. The PTO converts this to a continuous and relatively high frequency output signal usable by alternators.

Chapter 3

Project Background

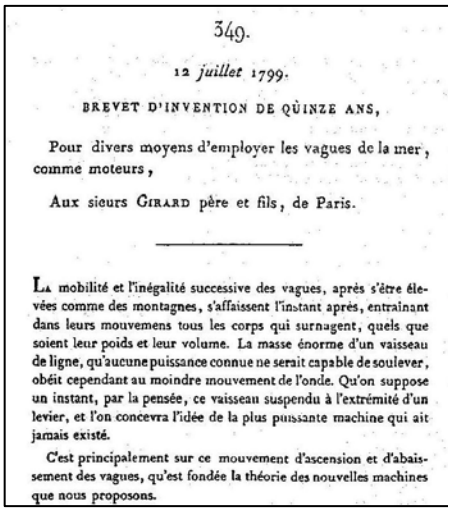
This section presents an overview of the ocean energy technologies, their classification and some current commercial-scale convertors. Discussion on the near-to-shore location and flap-type WEC is separately included due to Wing-Wave. In the last part of this chapter, the research done at Florida Tech on ocean energy is described.

3.1 History

The first recorded patent for harnessing ocean energy was filed in Paris by P.H. de Girard and his son in 1799 (French patent no. 349) (Polinder and Scuotto 2005).

Pioneering work for the modern wave energy technology was by a Japanese naval commander, Yoshio Masuda, in 1940's and 50's. His work includes the early design of Oscillating Water Column (OWC) and self-powered navigation buoys (Polinder and Scuotto 2005).

First wave of interest in ocean wave energy was triggered by the oil crisis in 1973. Severe oil shortage forced governments in Northern European countries to initiate big-scale research projects for alternate energy resources including wave energy.



349.

12 *juillet* 1799.

BREVET D'INVENTION DE QUINZE ANS,

Pour divers moyens d'employer les vagues de la mer, comme moteurs,

Aux sieurs GIRARD père et fils, de Paris.

LA mobilité et l'inégalité successive des vagues, après s'être élevées comme des montagnes, s'affaissent l'instant après, entrainant dans leurs mouvemens tous les corps qui surnagent, quels que soient leur poids et leur volume. La masse énorme d'un vaisseau de ligne, qu'aucune puissance connue ne serait capable de soulever, obéit cependant au moindre mouvement de l'onde. Qu'on suppose un instant, par la pensée, ce vaisseau suspendu à l'extrémité d'un levier, et l'on concevra l'idée de la plus puissante machine qui ait jamais existé.

C'est principalement sur ce mouvement d'ascension et d'abaissement des vagues, qu'est fondée la théorie des nouvelles machines que nous proposons.

Figure 3-1: Patent by Girad in 1799 (Polinder and Scuotto 2005)

In 1974 Salter's duck or nodding duck, invented by Stephen Salter at University of Edinburgh, was able to show up to 81% efficiency (Cruz 2008). Among other prominent researchers of that time were Johannes Falnes from Norwegian Institute of Technology and Michael E. McCormick from the U.S. Naval Academy. In 1981, McCormick authored the book 'Ocean Wave Energy Conversion' (Michael E. McCormick 1981) which is considered as the leading work in this field.

In the 1980s, as the oil price industry regained stability, both the immediate need and the funding for wave-energy research was drastically reduced. Between 1980's and 2000, though the research work was being carried on by the individual researchers and academic institutions, there was no major drive from the governments.

This situation changed in the 2000's for the ocean energy when global warming and depleting oil resources generated a global interest for renewable energy including ocean energy. In 2011, for the first time, the investment in renewable energy surpassed that in the fossil fuels for the new power-plants in USA[2].

[2] <http://www.bloomberg.com/news/2011-11-25/fossil-fuels-beaten-by-renewables-for-first-time-as-climate-talks-founder.html> Web accessed: 20-July-2013

3.2 Classification

There is a wide range of concepts and applications that can be used for the energy extraction from ocean waves. This is the reason wave energy can be classified into many types. Major classifications used generally are as following (Pecher 2012):

1. Fundamental physics
    a. *Terminator:* These gather a wave's energy and stop the forward propagation of the wave.
    b. *Attenuator:* These 'attenuate' the wave. These are generally surface float-type hinge-connected units.
    c. *Point Absorbers:* These are stationary devices and work on the differences in pressure and/or elevation in the surface of the ocean.
    d. *Overtopping Devices:* These collect and fill water in a chamber and use the potential energy of stored water.
    e. *Surge Convertor:* They capture the wave surge and have pitching movement about a hinge.
2. Location
    a. *Shoreline:* These are placed on the seafloor in shallow water or integrated in breakwater-like structures.
    b. *Near-to-shore:* These are deployed in up to 20m deep water, between 1-10 kilometers away from the shore.
    c. *Offshore:* These are kept floating or submerged in deep waters and are moored to the seafloor. These are exposed to the extreme harshness of the sea environment.
3. Operating Principle or Force
    a. *Buoyancy force*
    b. *Wave force*
    c. *Pressure differential*
4. PTO Type:
    a. *Air/ Water turbine*
    b. *Pressurized hydraulics*
    c. *Mechanical*
    d. *Linear generators*

Figure 3-2 and Figure 3-3 show the classification proposed by (Falcão 2010) and their illustrations.

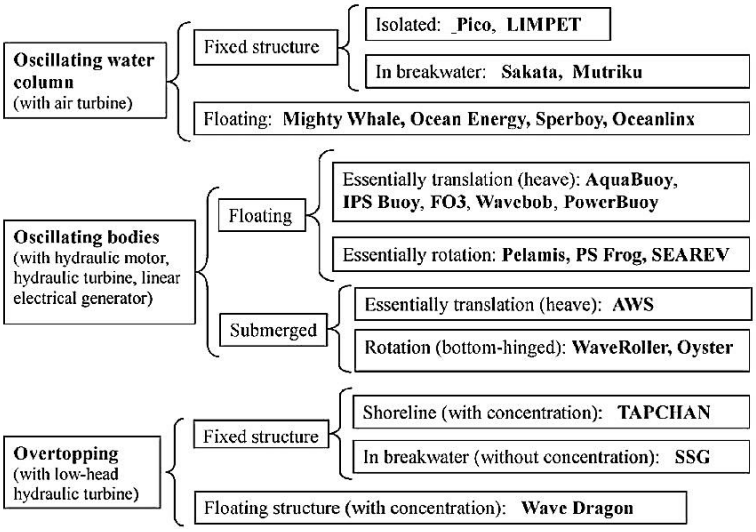

Oscillating water column (with air turbine)
Fixed structure
Isolated: _Pico, LIMPET
In breakwater: Sakata, Mutriku
Floating: Mighty Whale, Ocean Energy, Sperboy, Oceanlinx
Oscillating bodies (with hydraulic motor, hydraulic turbine, linear electrical generator)
Floating
Essentially translation (heave): AquaBuoy, IPS Buoy, FO3, Wavebob, PowerBuoy
Essentially rotation: Pelamis, PS Frog, SEAREV
Submerged
Essentially translation (heave): AWS
Rotation (bottom-hinged): WaveRoller, Oyster
Overtopping (with low-head hydraulic turbine)
Fixed structure
Shoreline (with concentration): TAPCHAN
In breakwater (without concentration): SSG
Floating structure (with concentration): Wave Dragon

Figure 3-2: Different types of Wave Energy Technologies (Falcão 2010)

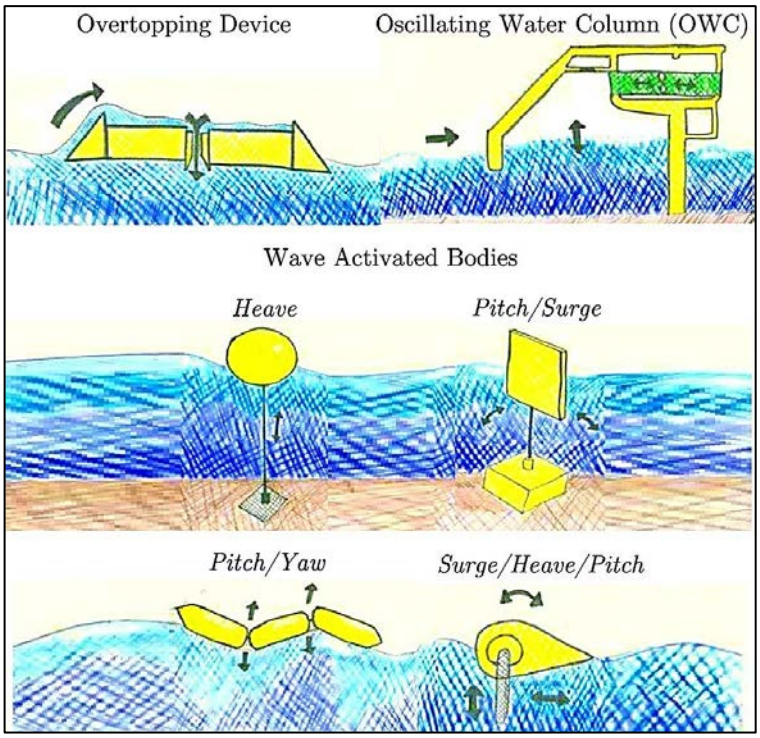


Figure 3-3: Illustrations for types of wave energy technologies (Pecher 2012)

3.3 Current Commercial-scale WEC

Table 3-1 presents some WEC that have been already launched or are being launched commercially in the last decade.

Device	Proponent	Country of origin	Capture method	Location	Year build
AquaBuOY	SSE Renewables Ltd	Ireland-Canada-Scotland	Buoy	Offshore	2003
AWS-iii	AWS Ocean Energy	UK	Surface-following attenuator	Offshore	2010
Oyster	Aquamarine Power	UK	Oscillating wave surge converter	Near-shore	2005
Pelamis	Pelamis Wave Power	UK	Surface-following attenuator	Offshore	1998
Wave Dragon	Erik Friis-Madsen	Denmark	Overtopping device	Offshore	2003
WaveRoller	AW-Energy Oy	Finland	Oscillating wave surge converter	Near shore	1999

Table 3-1: Some Prominent Commercial WEC

Figure 3-4: Photographs of commercial WEC (in order of Table 3-1)

3.4 Interest in Near-to-shore and Flap-type Convertors

Since Wing-Wave is a bottom-hinged flap-type convertor design for installation in near-to-shore, it is relevant to present the background of the recent developments for this type of WEC.

Historically, most research efforts and investment in the ocean energy technologies focuses on shoreline (oscillating water column devices) and offshore floating devices (Zhao et al. 2013). The main factors contributing to fewer near-shore devices are complications in design and maintenance issues. Also, in terms of potential wave energy, the near-shore locations are considered inferior to offshore regions.

However, recent studies show a promising future in near-shore devices. Folley and Whittaker demonstrate that although the total near-shore wave energy power is notably reduced as compared to off-shore the exploitable power is still significant (M. Folley and Whittaker 2009). Figure 3-5 presents a comparison of gross or total energy with the exploitable energy. In addition to this, near-shore area also offers comparative advantage of easy deployment, maintenance, and repair.

Flap-type bottom-hinged wave energy converters have been identified as an effective design for harvesting energy in near-shore locations. This design is categorized as 'oscillating wave surge converter; or OSWC by European Marine Energy Centre (EMEC). In last decade, many research publications have covered the theoretical aspects of mathematical model for Seabed-Mounted Bottom-Hinged Wave Energy Converters (E. Renzi, A. Abdolali, G. Bellotti 2012; M. Folley 2004; Porter and Biggs 2012).

Commercial prototypes of the flap type bottom-hinged wave energy converters have been developed and are under testing by Aquamarine Power Ltd (Oyster) and AW-Energy Oy Ltd (WaveRoller). Patents for these designs include the key design aspects for these WECs

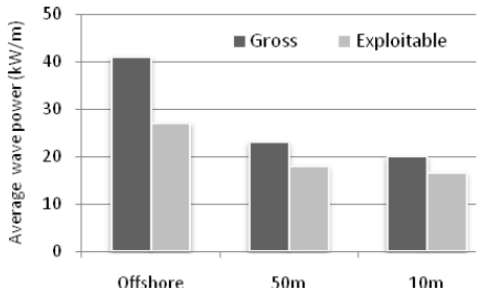


Figure 3-5: Average gross and exploitable wave power at three water depths (Cameron et al. 2010)

(Crowley 2012; Koivusaari 2007). A list of flap-type based WEC patents is presented in appendix 4.

3.5 Wave energy research at FIT

Before describing the wave energy research at Florida Institute of Technology (FIT), a brief note on marine resources for the state of Florida is presented.

The state of Florida has a coastline of 1,350 miles (2,170 km) which is the longest coastline in the continental United States. Potential generating capacity from ocean energy resources is estimated up to 10 GW (Driscoll et al. 2008) which is approximately one-third of Florida's average electricity consumption. Florida also sits next to the one of the strongest ocean currents in the world, the Gulf Stream, with a mass transport greater than 30 times the total freshwater river flows of the world. With all this potential, the 2013 energy profile of Florida depends more than 90% on the fossil fuels[3]. However recently, there has been legislation in process for increased share of renewable energies in the energy profile of state of Florida. Hopefully this will open up great opportunities for expansion in renewable energies in Florida in near future.

Florida Institute of Technology (FIT) is one of the prominent academic institutions actively working in the field of Ocean Energy in Florida since 2007. The Ocean Engineering Department at FIT is currently working on two prototypes Wave Energy Convertors (WEC): Wing-Wave, a sea-bed mounted bottom hinged type WEC that captures energy from the horizontal component of wave orbitals at varying depths, and GECCO, a surface floating attenuation WEC for harnessing surface waves.

In the next section, an overview of Wing-Wave's design and development since 2008 would be presented.

3.5.1 Wing-Wave

The main inspiration for Wing-Wave design is based on two commercial designs: Wave Roller by AW-Energy Oy[4] and Oyster Wave Energy Converter by Aquamarine Power[5]. Wave Roller's first prototype was launched in 1999. The Wave Roller is design for the installation underwater at the depths of approximately 8 – 20 meters. Oyster WEC works in the same fashion as the Wave Roller. The main difference is that the fluid in the hydraulic system is transferred onshore to a hydroelectric power plant. The second generation design of Oyster is rated up to 800kW (Power 2012).

[3] Source: U.S. Energy Information Administration (EIA) Web: http://www.eia.gov/state/data.cfm?sid=FL
[4] Web: <http://aw-energy.com/> Accessed: 20-July-2013
[5] Web: <http://www.aquamarinepower.com/> Accessed: 20-July-2013

Wing-Wave development started in 2008 as senior design project. As a first step, small models were built to figure out the best design for the maximum wave energy capture. Four tank-scale models were built and tested in a wave tank for their range of motion as following:

1. Flat wing
2. Flat wing with a top panel (T-shaped)
3. Triangular wing
4. Flat panel with top and side panels

Most effective capture design was the wing with top and side panels. This model design was finalized for the sea-test scale prototype wing.

In 2010, Clean and Green Enterprise sponsored the construction of Wing-Wave. This large-scale Wing-Wave prototype was built using two 15' x 8' tall aluminum wings placed one in front the other connected to the frame via stainless steel hinges. The dimensions of the base were 20' x 15', constructed of 6061 Aluminum. Due to unexpected storm weather during deployment, the unit was damaged and not fully tested.

In 2011, a single flat composite wing 6' tall x 4' wide, connected to a smaller steel frame via a large stainless steel hinge. Deployment was successful and showed that the Wing-Wave was a viable means of producing ocean energy. The onboard accelerometers recorded

Figure 3-6: (Top Left, Clockwise) Wing-Wave Prototypes for year 2008 (model), 2010, 2011 and 2012/13

movement up to $\pm 30^{\circ}$.

Due to successful working of 2011 prototype Wing-Wave, the same design was continued in 2012. A similar sized composite wing was added in the design. So the combined dimensions of the unit were 6' tall x 8' wide. Resin $\frac{1}{2}$" thick with alternating prism support beams, 8" wide bases and 6" wide top were used. The approximate weight of each panel was 150 lbs. The wings were attached to an aluminum frame which was bolted directly to the sea floor via sand screws. This design was again successfully deployed in summer 2012 and 2013. For these deployments, Wing-Wave was connected to PTO system (this thesis) details of which are presented in the next section. Figure 3-6 shows the pictures of Wing-Wave from 2008 to 2013.

Part II

Hardware Design and Construction

Chapter 4

Methodology

Earlier deployments of WEC by Ocean Engineering department, Florida Tech were focused on the concept verification of the WECs, which was demonstrated successfully. One of the main goals of work in 2012 and 2013 on the Wing-Wave was to develop a basic setup for the evaluation of the electrical generating potential of the device. In addition to this, operational data acquisition was desired to understand and identify the areas for further design improvements. This section presents the details of the design and components selection for both first (2012) and second (2013) PTO prototype.

4.1 Design Requirements

The principal requirement regarding the testing and performance evaluation of prototype WEC's was to design and develop a modular system for the energy conversion from WEC, safe dissipation of the generated energy and logging of the real-time system parameters (electrical and process) for analysis.

There were number of issues which had to be kept in mind while designing the system:

1) Time availability
2) Budget
3) Deployment Issues
4) Access for troubleshooting
5) Potential loss of device and data
6) Team Experience

There is always a factor of uncertainty and tough engineering constraints when it comes to the oceanic environment. With the sensitive electrical and control components, where a small mechanical shock or minor moisture ingress can result in permanent loss of devices, the design criterion becomes more complicated. A simple failure could cost heavily in terms of time loss or functionality due to limited access.

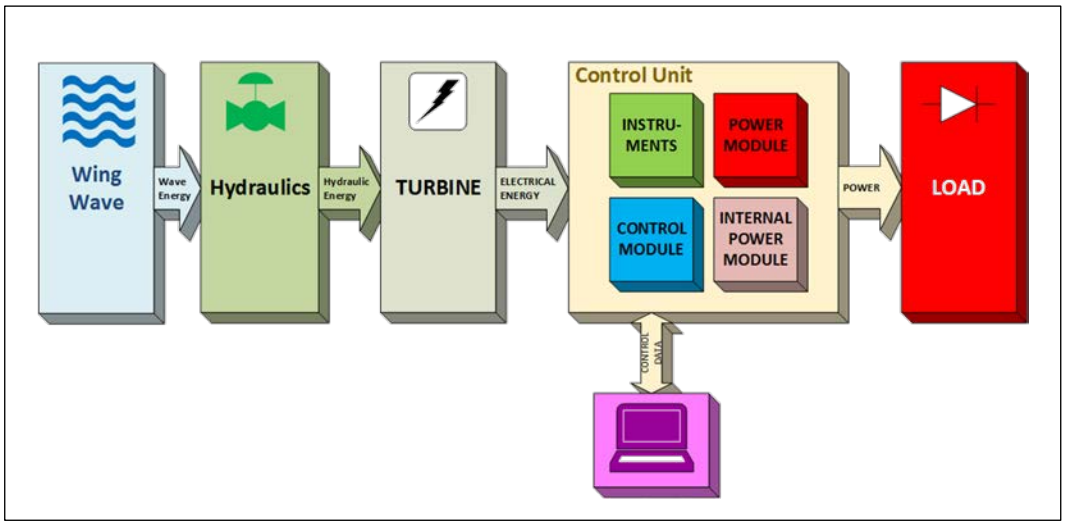


Figure 4-1: Functional block diagram of the project

To make things workable within the time and budget constraints, the following approach was selected:

1) Robustness and seaworthiness
2) Modularity to facilitate troubleshooting and further development.
3) Minimum maintenance during operation (a major lesson learnt from old deployments)
4) Remote connectivity to view real-time operational status
5) Data backup plans (both local and remote)

One additional aspect of this project was the fact that the primary element was underwater. This made problem identification relatively hard and tedious because of access limitations. Carrying cables from sea floor to surface is not easy due to unpredictable sea states.

Attempts were made to consider all the above points in the final design. Figure 4-1 presents a modular overview of the project.

Figure 4-1 shows the energy flow through the overall project. Wave energy from the WEC (Wing-Wave) is converted to hydro-mechanical energy by hydraulic part of the Power Take-off system. Then it is converted to electrical energy through the Pelton turbine and coupling alternator. The power module of the main control unit regulates and conditions it for the system test load. The control and data acquisition module system controls the hardware, logs all instrumentation data locally, and transmits it wirelessly to the remote user workstation. The power take-off system and control unit are housed on the PTO raft,

anchored near the WEC during the deployment. The PTO raft is designed so as to protect the sensitive electrical and hydraulic components from the harsh marine environment.

In following sub-sections, methods for each block are explained with the details of both first and second prototype of PTO system.

4.2 Power Take off System – Control Design

4.2.1 Control and Data Acquisition Module

The key functions of the control unit in the PTO were:

1) Interfacing of all sensors
2) Implementation of control algorithm through actuators
3) Local data logging of sensor data
4) Provision of an communications interface
5) Display of operational parameters on user workstation (HMI)

In addition to the above, there were other factors that were considered: reliability, flexibility, and cost. Different design approaches were opted for the first and second prototype design. For the first one, off-the-shelf indusrtrial controller or PLC was used.

Although custom-designed microcontroller based single-board computers offer great benefits in terms of cost and customization, the time required for design maturation and testing is long. Time was one of the major concerns for the first prototype. With off-the-shelf available industrial-grade control unit or Programmable Logic Controller (PLC), which includes the general purpose I/O interface and easy-to-use programming environment, the development time is reduced. But PLC's are expensive. In the end, the PLC was used, thanks to a donation of the control units by Intech Automation[6].

The PLC selected is a Cellular Micro-RTU Controller ioLogik W5340 by Moxa Corp[7]. This unit, in addition to analog and digital interfaces, supports GPRS technology for cellular remote monitoring and alarm systems. Moxa's RTU controllers can log data through I/Os and serial interface to a single, expandable SD card slot (up to 32-GB) and provide multiple methods to remotely retrieve data logs, whether through FTP, e-mail or OPC based software. For additional analog inputs, *ioLogik E1240* (Ethernet Remote I/O) is used. This

Figure 4-2: (Left) Control and data acquisition System (Middle) Moxa® W5340i Controller (Right) ActiveOPC Server software

[6] Texas based Automation company, Intech Process Automation <www.intechww.com/>

[7] User's Manual for ioLogik Cellular Micro RTU Controller By Moxa® Inc. <www.moxa.com/product>

unit also provides built-in 2-port Ethernet switch for daisy-chain topologies.

Figure 4-3 shows the overall control diagram. The control unit RTU Controller W5340, Ethernet I/O card E1240, signal conditioning card and marshaling terminals. Control supply is provided by two 12-V panel batteries (one for control units and one for the solenoid valves). All these components are placed in an IP-67 rated weatherproof housing.

The control unit acquired and stored the data from instrumentation locally on a 16-GB memory card. Then the data is sent to the internet using the cellular network in real-time. This data is sent to the main server (AMD A8 1.5-GHz processor) located at the Florida Institute of Technology with a fixed IP address.

The communication protocol used is based on an open standard OPC. The software hierarchy[8] is as follows:

1) *IOAdmin™* (configuration and diagnostic software)
2) *ActiveOPC™* (OPC server software for connectivity)
3) *DA-Center™* (OPC client software for data-logging)
4) FTP server

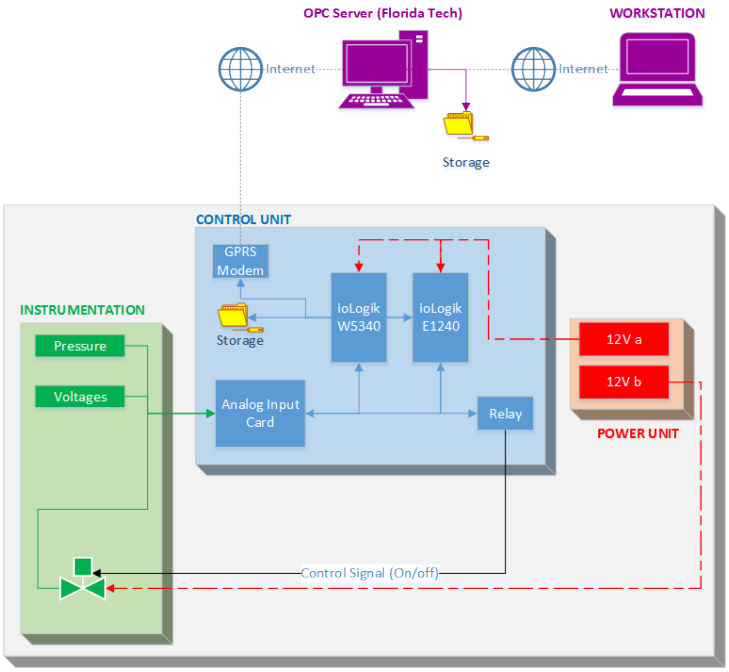


Figure 4-3: Control Diagram for the first deployment

[8] IOAdmin™, ActiveOPC™ and DA-Center™ are proprietary software for Moxa RTU.

5) Web server

The main server stores all the data received and then updates all values on a webpage. This was accessible to the user via internet (updated every 1 second in real-time). This way, the end user is able to monitor the operational status using this live feed from PTO raft.

For the second prototype, a microcontroller based two-layered control system was selected. Raspberry Pi (Model B) was finalized as the master controller and Arduino ATmega2560 as the slave controller. Both of these controllers are based on open-source hardware The overall control diagram is presented in Figure 4-4.

Raspberry Pi is an ARM (Advanced RISC Machine) based single-board computer developed by the Raspberry Pi Foundation9. Model B version comes with 512 megabytes of RAM, and supports an SD card (up to 32GB) for booting and long-term storage. It also supports video and audio outputs for user interface. The Raspberry Pi uses Linux kernel-based operating systems. Raspbian[10] (a Debian-based free operating system) was used for this prototype. Table 4-1 shows specifications for Raspberry Pi Model B. One more feature is that there is support for Matlab/Simulink (xPC target tool box) which means that Matlab code can be downloaded in Raspberry Pi and executed in real time. For programming and debugging,

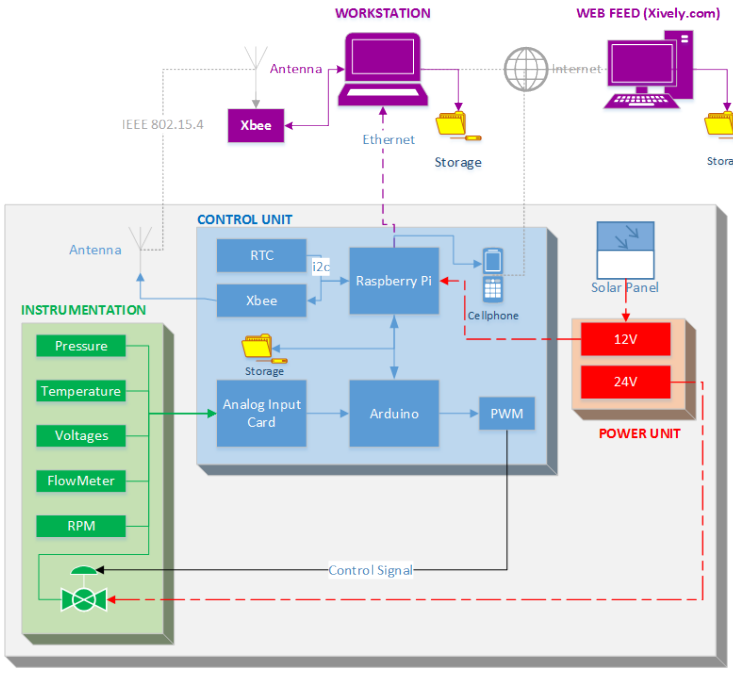


Figure 4-4: Control Diagram for the second deployment

[9] http://www.raspberrypi.org/
[10] http://www.raspberrypi.org/downloads

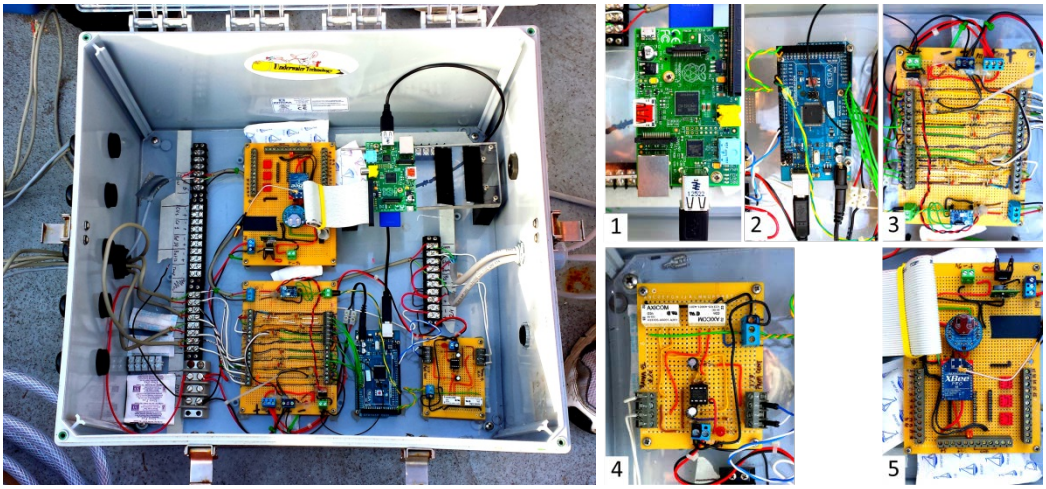


Figure 4-5: (Right) Control panel for the second deployment (Left) Close-up shot of cards (1) Raspberry Pi (2) Arduino (3) Analog Input Card (4) PWM/Relay Card (5) RTC and Xbee Card

Adafruit's Web IDE 2.0 was used. All the code was written in Python.

Though Raspberry Pi has support for peripherals like general purpose IO's, I^2C bus and SPI bus, but lacked some important provisions required for this project (e.g. pulse-width modulation (PWM), analog digital converter (ADC) and Real Time Clock (RTC)). For this reason, the Arduino (as support or slave controller) and a dedicated RTC shield are used with the Raspberry Pi.

SoC (System on chip)	Broadcom BCM2835
CPU	700 MHz ARM1176JZF-S core (ARM11 family)
GPU	Broadcom VideoCore IV @ 250 MHz
Memory (SDRAM)	512 MB
USB 2.0 port	2
Onboard storage	SD / MMC / SDIO card slot
Onboard network	10/100 Ethernet
Low-level peripherals	8 × GPIO, UART, I^2C bus, SPI bus
Power	700 mA (3.5 W)
Power source	5 volt
Size	85.60 mm × 53.98 mm (3.370 in × 2.125 in)
Operating systems	Arch Linux ARM, Debian Linux, Raspbian OS, RISC OS

Table 4-1: Specifications for Raspberry Pi Model B (Richardson and Wallace 2012)

Core	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (15 PWM output)
Analog Input Pins	16
DC Current per I/O Pin	40 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB (8 KB used by boot-loader)
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

Table 4-2: Specifications for Arduino AT Mega2560 (Arduino 2013)

The Arduino Mega 2560 is a derivative of Arduino family. The Arduino[11] is an open-source electronic hardware prototyping platform. The core of this board is ATmega2560[12]. This board supports a large number of IO's, both analog and digital, making it an ideal choice for hardware interfacing. It also has 4 hardware serial ports (UARTs). Arduino programs are written in the dedicated IDE in C or C++. Arduino comes with a pre-programmed on-chip flash memory with a boot loader. Due to this in-system programmability, no external hardware is required for programming.

Since a timestamp is required for the recorded data for later viewing and Raspberry Pi has no real-time clock, a dedicated RTC shield 'ChronoDot' is used. This is based on the DS3231 temperature compensated RTC (TCXO). It uses a 3.3V CR2016 battery as backup that can last up to 8 years. The device interface is I^2C bus. The device default address is x68. Due to built-in temperature compensation, the drift rate is less than a minute/year.

A custom analog interface card was built to interface Arduino and Analog inpauts for them instruments. A PWM/Relay card is used for the control signals. An RC filter is used to convert PWM signals (frequency approximately 500 Hz) to analog volatges that is scaled to 0-10V using TL072CN Opamp. Details of instrumentation are in next section.

The Raspberry Pi is connected to the Xively.com, a cloud platform service, via internet using cellphone. Xively.com is a public on-line database alloiwng users and developers to connect and upload all the data from their devices and instruments to the web, and to use in their applications [13] . The link for the live web feed for this project is *https://xively.com/feeds/1480855249*. This webpage can be viewed by any user on internet.

[11] Web: <http://arduino.cc/en/Main/arduinoBoardMega2560>
[12] Web: <http://www.atmel.com/dyn/resources/prod_documents/doc2549.pdf>
[13] Web: <https://xively.com/whats_xively/> Accessed: 20-July-2013>

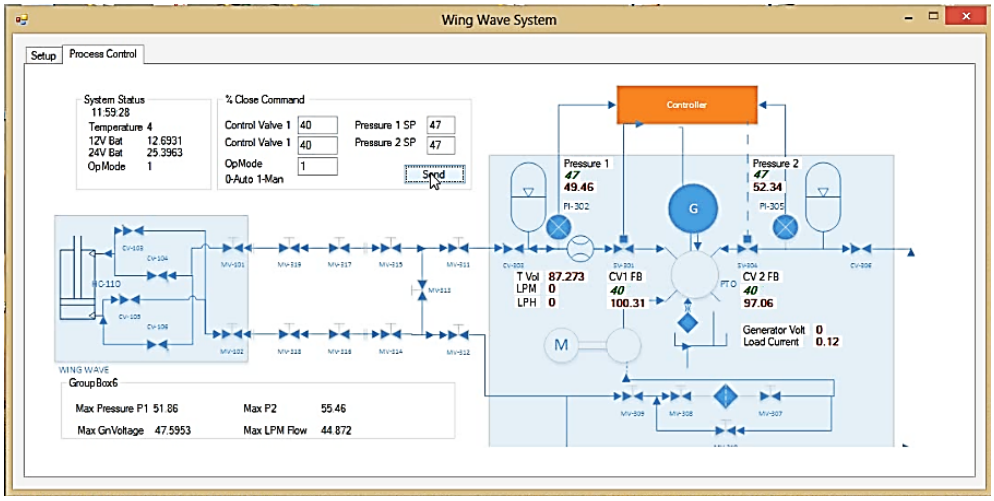


Figure 4-6: Visual Basic based HMI

An Human Machine Interface (HMI) system was developed in Microsoft Visual Basic to view the results from the control system in real-time. Figure 4-6 shows the user interface. This HMI is run on the user station in the research vessel and is connected to the main control system using Xbee RF module (details in communication section later). This software has both a graphical interface (using system piping and instrumentation diagram) and a simple textual interface.

The summary of the control system design is as follows: The Raspberry Pi acts as the main controller and performs all the communication, and logging functions. The Arduino handles the analog inputs and control signals. The Arduino sends the updated the I/O map in every cycle to the Raspberry Pi which in turn is sent to the main user station via Xbee RF module and to the web feed using hotspot through a cell phone. User can send values for operational mode (Auto or manual), pressure setpoints (Auto mode only) and control valve positions (Manual mode only).

4.2.2 Instrumentation

This controller is interfaced with the instrumentation for WEC including pressure, generator output voltage/current and the panel's internal battery voltage. A flow meter, temperature and RPM sensors, were added in prototype 2. Solenoid valves and proportional control valves along with instrumentation were used as actuators in first and second prototype respectively.

Table 4-3 and Table 4-4 summarize the instrumentation and actuators used with the PTO prototype 2.

#	**Instrument Description**	**Range**	**Unit**	**Type**	
1	Pressure 1	0-200	PSI	4-20 mA	
2	Pressure 2	0-200	PSI	4-20 mA	
3	Generator Output Voltage	0-60	V	0-60 V	
4	Current (Load)	0-5.0	A	0-5.0 V	
5	RTD Temperature	0-100	C	0-2.5 V	
6	12V Battery Voltage	0-13	V	0-13 V	
7	24V Battery Voltage	0-25	V	0-25V	
8	Control Valve 1 Position	0-100	%	0-10V	
9	Control Valve 2 Position	0-100	%	0-10V	
10	Flow meter	1-114	LPM	Pulse	
11	Proximity Sensor for RPM	0-3000	Pulse	Pulse	

Table 4-3: Input Map

S. No.	**Instrument Description**	**Range**	**Unit**	**Type**	
1	Control Valve 1 Command	0-100	%	0-10V	
2	Control Valve 2 Command	0-100	%	0-10V	
3	Control Valve 1 Force Close	-		Digital	
4	Control Valve 2 Force Close	-		Digital	

Table 4-4: Output Map

Industrial-grade general-purpose 4-20mA pressure transmitters[14] by Wika™ are used for pressure measurement. All wetted parts are made in stainless steel 316L. The range is 0 to 1,379-kPa (or 0 to 200-psi) with ±0.5% accuracy.

For flow measurements, a paddlewheel based flowmeter[15] (RotorFlow RF-2500 Model: 194761) from GEMS Sensors is used. The sensor provides high speed pulses from an integrated Hall Effect sensor in the flowmeter. This can measure up to 30 Gallons/minute or 114 liters per minutes with ±15% accuracy. Housing and wetted parts are made of brass. One help feature is a glass panel on the wheel side that helps visual confirmation. For the interface with control system, FLO-30 card from Atlas Scientific is used. This card measures the incoming pulses from flowmeter and sends the calculated values for total volume, flow in LPM and flow in LPH in serial format.

For measurement of generator output voltage, battery voltage and load current, a simple voltage divider based signal conditioning card is used as input for the controller.

In deployment 2012, ½" solenoid valves (12Vdc; Normally Closed 2-way; Stainless Steel) are used for controlling the flow in the hydraulic system. In 2013, these are replaced with size: 3/4'' proportional control valves[16] by Winner valves. The valves are ¾" ball type, equal percentage flow. Actuator is motorized (24Vdc operated; Torque up to 6 N.m). It supports control signal of 0-10V and 4-20mA. Position feedback is given by a potentiometer. Full closure and opening time is between 55-60 seconds. Power rating for these valves is 12V-A.

To measure the speed of generator, an RPM Sensor was built using inductive proximity switch (Model: PR12-2DN Range:2mm Speed:1.5kHz) by Autonics. However due to

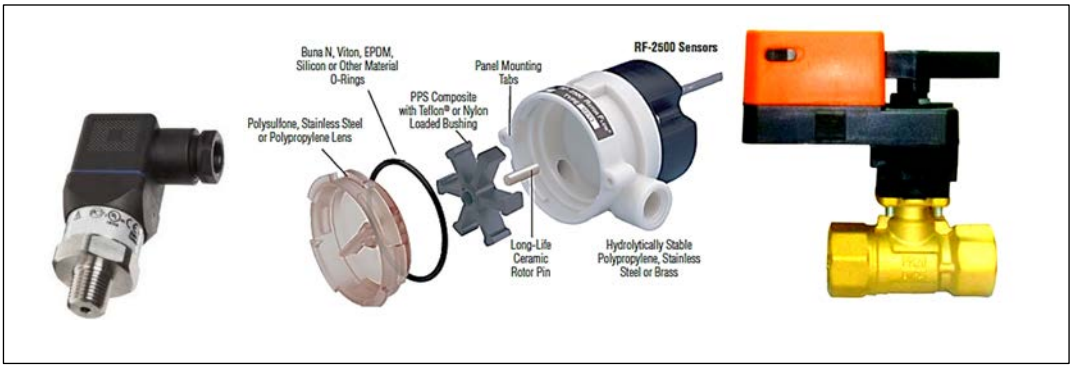

Buna N, Viton, EPDM, Silicon or Other Material O-Rings
Panel Mounting Tabs
RF-2500 Sensors
PPS Composite with Teflon® or Nylon Loaded Bushing
Polysulfone, Stainless Steel or Polypropylene Lens
Long-Life Ceramic Rotor Pin
Hydrolytically Stable Polypropylene, Stainless Steel or Brass

Figure 4-7: (Left) Pressure Sensor (Middle) Exploded view of Flowmeter (Right) Proportional Control Valve

[14] Datasheet for Wika Pressure Transmitters Model 50398083
[15] Atlas Scientific
[16] Model:WVA4-306-k+WCBS220 by Winner Ball Valves (China)

mechanical mounting issues, it was not used in the deployment.

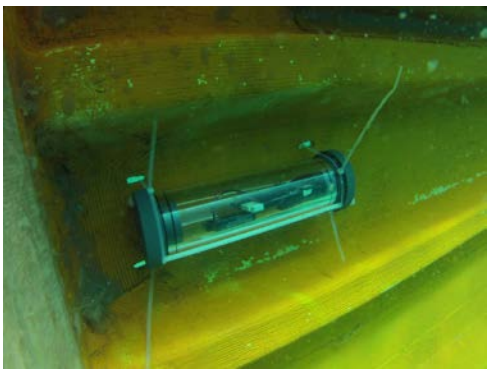


Figure 4-8: Accelerometer

In addition to the above, a standalone Accelerometer is used to record the movements of the Wing-Wave during deployment. This unit is designed by Mathew Jordan [17] . It uses a triple axis accelerometer ADXL345 by Analog devices interfaced a micro Arduino (Teensay[18]) and OpenLog data logger by SparkFun. It recordes the accelerations of Wing-Wave and translated it to angular displacement (in degrees).

[17] a Masters student in Ocean Engineering at FIT, mjorda01@my.fitt.edu

[18] http://www.pjrc.com/store/teensy3.html

4.2.3 Communication

In the control system there are three levels of communication interfaces. At the first level, Arduino and Raspberry Pi are interfaced to communicate through standard serial port. At second level, an RF modem, Xbee PRO, is used between Raspberry Pi and user station. Further at third level, Raspberry Pi uses GPRS for internet connectivity via cellular phone to send data for live web feed (already described in earlier section).

At first and second level, same format for data packets are used as shown following:

Instrument Data packet:

```
P1=20.19 P2=23.42 GV=20.90 Cur=0.00 T=0.00 B12V=12.56 B24V=24.59 CVFB1=45.00
CVFB2=47.00 CV_CMD1=20 CV_CMD2=20 FT=0.057 FLPM=0.000 FLPH=0.000 OPMode=1 <\r><\n>
```

Control Data Packet:

```
ControlValve1Setpoint ControlValve2Setpoint PressureSetpoint1 PressureSetpoint2
OperationMode <\r><\n>
```

`<\r><\n>` represents carriage return and new line characters. An example for control packet: to send command for both valves 100% closed, 50 PSI for both pressure setpoints and Auto mode, packet would be `100 100 50 50 0 <\r><\n>`. AlphaNumeric format for instrument data packet are selected for easy troubleshooting in the field and to allow use of textual terminal emulators.

The component used for field-level wireless connectivity is a XBee-PRO [19] by Digi International. XBee modules use the IEEE 802.15.4 networking protocol at 2.4GHz for fast point-to-multipoint or peer-to-peer networking. The unit selected is rated up to 60mW and could support connectivity up to 1 mile. Baudrate for communication is 9600 bps. An external antenna was used with PTO raft for better reception.

4.2.4 Control Algorithm

This section presents the pseudo-code for the Arduino and the Raspberry Pi controller.

Pseudo-code for Arduino Controller:

```
SETUP (){
        Initialize Onboard_Hardware
        Initialize Serial_Ports
        Initialize Control_Valves in CLOSE_POSITION
        }
```

[19] Web: <http://www.digi.com/products/wireless-wired-embedded-solutions/zigbee-rf-modules/point-multipoint-rfmodules/xbee-series1-module#overview> Accessed: 20-July-2013

```
LOOP (){
        Check SerialPort1 for Input from RASPBERRYPI
        IF      DataPacket is legit
        Then    Update Command_Signal_Variables

        Check SerialPort2 for Input from FLOWMETER
        IF DataPacket is legit
                Then Update Flow_Variables

        Read all Analog_Input_Varaibles

        If      Mode is AUTO
        Then
                STEP1:  If      Pressure > Pressure_SetPoint
                        Then    Open ControlValve 80%
                STEP2:  Elseif  GeneratorVoltage > 15V
                        Then    Open ControlValve 40%
                STEP3:  Elseif  GeneratorVoltage > 15V
                        Then    Close ControlValve

        ElseIf  Mode is Manual
        Then    ControlValve Opening = Command_Signal

        Send DataPacket on SerialPort1 to RASPBERRYPI
        }
```

Pseudo-code for RaspberryPi Controller:

```
SETUP:
        Initialize Onboard_Hardware
        Initialize Serial_Ports
        Create New Data_File


LOOP:
        Check SerialPort1 for Input from Xbee
        IF      DataPacket is legit
        Then    Update Command_Signal_Variables
                & Send Command_Signal_Variables on SerialPort2 to ARDUINO

        Check SerialPort2 for Input from ARDUINO
        IF      DataPacket is legit
        Then    Update All_Input_Variables
                & Send All_Input_Variables on SerialPort2 to Xbee

        Save All_Input_Variables and Command_Signal_Variables in FILE Data_File
        Add TimeStamp in FILE Data_File

        Send All_Input_Variables and Command_Signal_Variables to WEB_LIVE_FEED

        REPEAT LOOP
```

4.3 Power Take off System – Electrical Design

Due to time and resources limitations, a simple power electronics design is selected to demonstrate the operation of Power module. The purpose of this module is (1) to regulate the electrical output of the power take-off system as per provided load requirements and (2) to protect the system load from unsafe voltage levels.

Output from Harris® generator is rectified using a diode bridge[20] and then through a charge controller NC25A (FlexCharge®), it is fed to the test load. The charge controller steps down the generator output voltage to 12 or 24-V depending on mode selected. The test load consists of a primary load (12-V/80-AH battery) and a secondary/diversion load (a fixed power resistor). It dissipates the electrical power produced by the generator. The electrical energy is directed first to the primary load (battery) and then after the battery is charged, to a secondary load (resistor).

The charge controller is selected due to weather-proof enclosure and suitability for the marine and alternative energy systems. It can handle up to 25A of load current and can protect the load from voltage surge up to 140-Vdc[21].

4.3.1 Control Supply and solar panel

One major issue faced in the 2012 deployment was the draining of control supply battery during the deployment. For this reason, a 15W/1A solar panel[22] is included in the design for the main control supply.

Control supply is provided by a 70AH/12V and two cascaded 35AH/12V lead-acid batteries. The 70AH is for the main control panel and the two 35AH are for the 24V supply of control Valves only. Approximate current consumption for typical usage of the control components is presented in Table 4-5.

[20] M50 Diode Series by Crydom < http://www.crydom.com/en/products/catalog/m_50d.pdf >
[21] FlexCharge USA. <www.flexcharge.com/flexcharge_usa/products/nc25a/nc25a.htm>. Web Accessed: 12 May 2012.
[22] Motomaster Eliminator <http://www.toolfetch.com/media/documents/38318.pdf>

#	**Component**	**Current (mA)**	
1	Raspberry Pi	*700*	
2	Arduino[1]	*200*	
3	Pressure Instrument (02)	*50*	
4	Xbee Pro 60mW	*215*	
5	Relays (02)	*80*	
6	Flow meter	*12*	
7	Misc board components	*50*	LEDs, regulators etc.
	Net (Main Control Panel)	**1307**	
7	Control Valves (02)	500	Assuming 50% load in an hour (500mAh at full occupancy)

Table 4-5: Current Consumption

So for the given current consumptions, batteries will last for (without solar panel):

$$70\text{Ah}/1.37\text{A} = 53.5\ \text{Hours} \cong 2.2\ \text{Days}$$

And

$$35\text{Ah}/0.5\ \text{A} = 70\ \text{Hours} \cong 3\ \text{Days}$$

So the battery sizing is enough for 2 days deployment for the typical consumption without backup power supply.

4.4 Power Take off System – Hydraulic Design

The hydraulic design part of the power take-off system is responsible for the conversion of wave energy to the hydro-mechanical energy. Both mechanical and hydraulic systems were considered for PTO mechanisms. Hydraulic system was opted due to cost-effectiveness and ease of construction. Hydraulics system also provides a simple way to interface and test different types of WECs (which was a requirement for the deployment in 2012).

As described earlier, first prototype was planned to be tested with both Wing-Wave and GECCO connected together. The circuit is designed to accommodate two hydraulicsf inputs. A similar approach however is used in the second deployment too as two pistons are used with the Wing-Wave. Further details of the deployment will be presented in Chapter 7.

The overall hydraulic schematic is shown in the following figure:

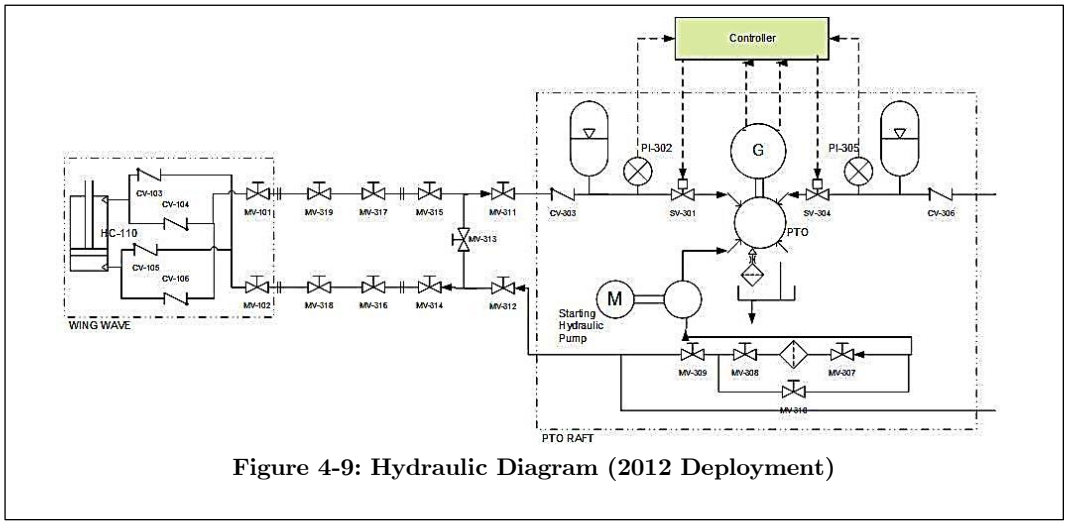


Figure 4-9: Hydraulic Diagram (2012 Deployment)

The design is based on a hydroelectric PM brushless alternator with Pelton turbine and hydraulics system to harness energy from the wave energy converters. This system resides in the PTO raft floating on the sea surface. Two double-acting hydraulic cylinders, coupled mechanically with the flap of the Wing-Wave, act as the primary elements of WEC. The hydraulic fluid (fresh water) is pumped up to the PTO raft through a submersible set of check valves installed at the Wing-Wave. An oil-filled pressure gauge is also added in the design so the divers can verify the pumping operation of the cylinders and identify any potential issue (for example leakage). In the PTO raft, low-pressure diaphragm-type air-charged accumulators act as temporary energy storage sources and suppress minor fluctuations in the pressure. These accumulators are charged up to 30 psi of air and have capacity of 36 gallons. Fluid flow is regulated using proportional control valves to the electrical generator. Pressure safety valves (rated 75 psi) are also installed in the system as

over-pressure protection in case of any component failure. Manual ball valves are installed in the system for the provision of isolation and by-pass operation via manual valve lineup. After the generator all hydraulic fluid is collected in 125 Gallon reservoir in the PTO raft connected to the return lines going to the Wing-Wave.

The hydro-electric generator is a Harris® hydrokinetic Pelton-wheel based impulse-turbine with 1.5kW rated PM brushless alternator[23]. The alternator efficiency is between 30% - 70% depending on the fluid flow and pressure. The turbine has provision for four nozzle inputs. Following figure shows the electrical output for given pressure head and flow.

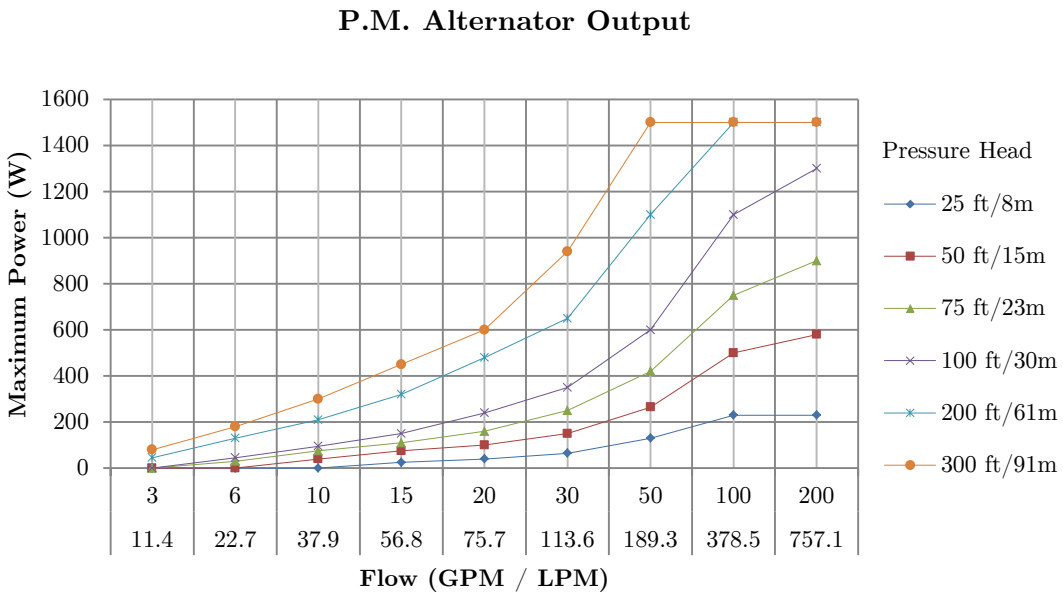


Figure 4-10: Output power for Harris generator

All piping used is of ¾" diameter. The pipe size is reduced to ½" at the nozzle inlet to increase the pressure for the Pelton turbine. Hoses used to connect Wing-Wave and PTO system are 3/8" and are approximately 70 feet long. Figure 4-10 shows the internal hydraulic system in the PTO raft.

[23] Harris® Hydro-electric generator <http://harrishydro.biz/><>

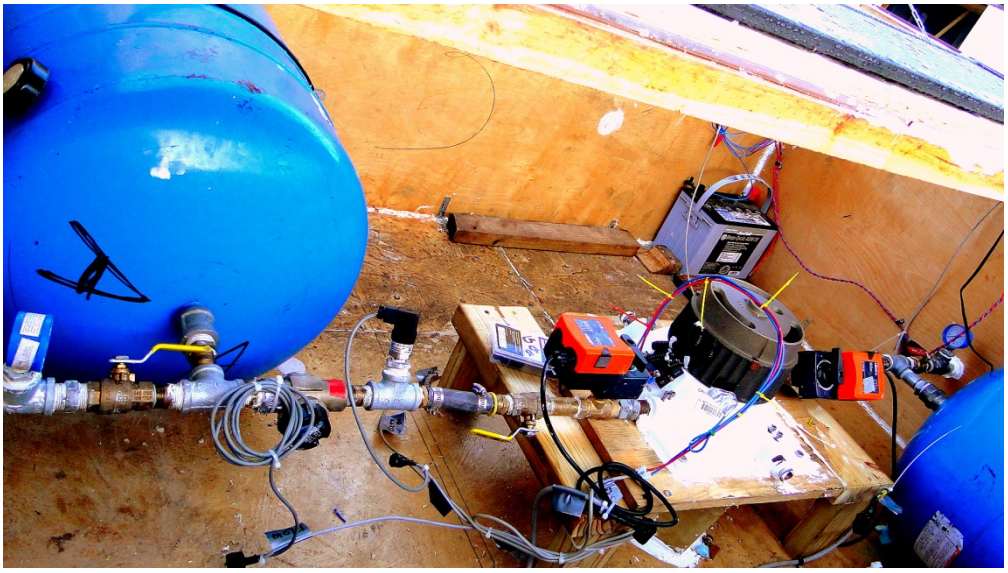


Figure 4-11: Hydraulic system in PTO raft (2013)

4.5 PTO Raft Design

In 2012, the PTO raft was designed as a floating vessel, shaped like a simple box, constructed of 0.64-cm ($\frac{1}{4}$-in) plywood with all body fiberglass coated. The finishing process was similar to a wood boat hull, in order to prevent water ingress into the vessel body. Angle 6061 aluminum was used along the edges of the housing to add structural strength. This allowed two people to stand on or in the vessel while still maintaining a minimal draft of about 10-cm (4-in). However during deployment it was found that the 2012 design had hydrodynamic issues and was not stable enough to do any maintenance activity properly.

In 2013, the design was totally changed. An Aluminum based frame (86"long x 72"tall x 68.5"wide) was used. Wooden compartment for the PTO system was made separately. Two 14' hulls and two 10' long 24" diameter pipes were used for the buoyancy. Pipes were filled with foam. The design provided good stability. It was made more spacious to accommodate any maintenance activity safely during deployment. FRP sheets were used outside the wooden compartment and resin costing was used in interior for water proofing.

Figure 4-13 and Figure 4-14 show the PTO raft constructed for 2012 and 2013 respectively.

Figure 4-13: PTO Raft Design (Deployment 2012)

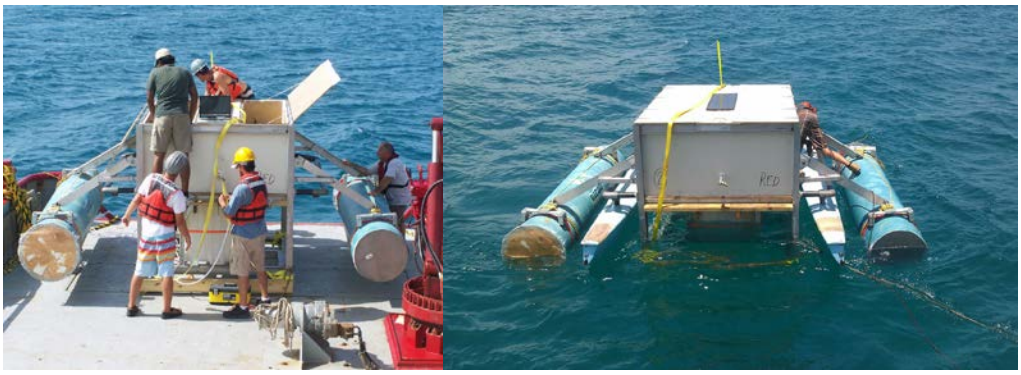


Figure 4-14: PTO Raft Design (Deployment 2013)

Part III

Testing and Deployment

Chapter 5

Laboratory Testing

This section presents the laboratory and land testing results for the Wing-Wave and PTO.

5.1 Generator Testing

One of the major design concerns initially was the unavailability of a proper technical datasheet (nameplate data, and maximum current/speed limitations etc.) for the Harris hydroelectric generator. The generator was mainly designed for low flow land-based applications. So it was necessary to verify the operation of the generator. For this purpose, mechanical and process testing of the Harris generator was done.

The generator was coupled with a mechanical rotational source (max speed 1500 revolutions-per-minute or rpm) using tachometer and voltmeter to determine rpm and voltage relationship. Figure 5-1 shows the relationship between speed and output voltage.

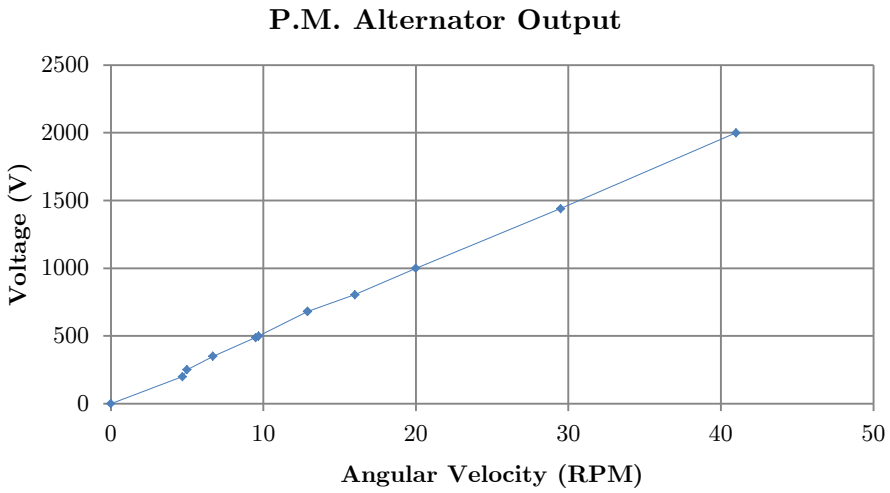


Figure 5-1: Results for the mechanical testing of Harris Hydroelectric Generator

For the process related parameters, the generator was setup in a wave tank and a centrifugal pump 1.12-kW (1.5-hp, 3450-rpm; 115/230 FLA 15.6/738A; 60-Hz) was used as input source. Figure 5-2 shows the recorded results that with approximately 90-kPa (13-psi), inlet pressure the generator started to operate with output of approximately 22-V (no load).

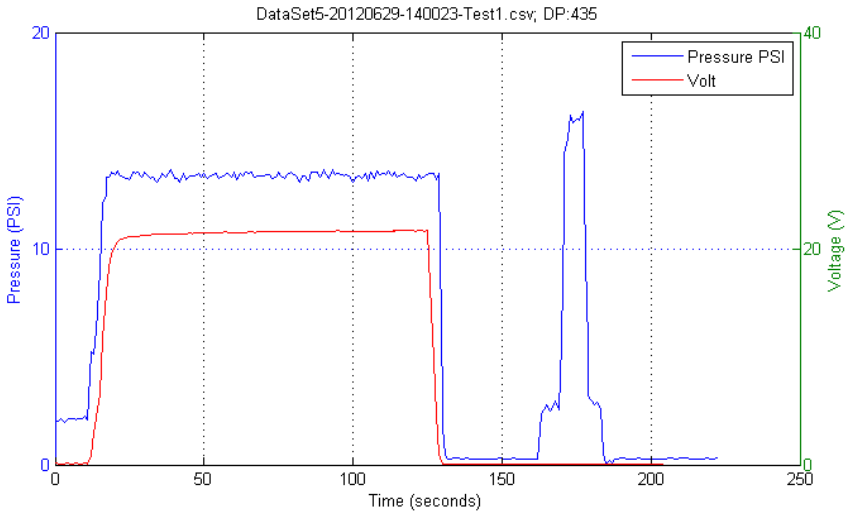


Figure 5-2: Results for the process testing of Harris Hydroelectric Generator

This hydraulic setup used a direct connection between the pump and the generator. Solenoid on-off valve were used. There were no accumulators in the system.

5.2 Wing-Wave and Piston Testing

It was important to understand and verify the practical performance of the Wing-Wave after the construction. For the integrated testing of the complete system, it was decided to move the flap manually, which was connected with the both pistons and the PTO system and simulate the movement of Wing-Wave underwater.

Two teams of three persons were on each side of the flap to push it. Wing-Wave was able to pressurize the PTO system up to 42 PSI in about 15 turns. Initial movement of flap was easy but as the pressure approached 40 PSI, it got difficult to move with the existing man power because of the hydraulic load on the pistons.

Figure 5-3: Land testing of Wing-Wave

5.3 PTO Testing

The PTO system was also tested separately for the performance evaluation. A utility water supply (50 PSI) was used to pressure the hydraulic system. Proportional control valves were used to control the flow. The PTO system successfully started the generator and was able to run it for approximately 100 seconds. Since the utility water is a high-pressure and low-flow system so these results were understandable.

The data set obtained is shown on the next page. Generator output voltage levels up to 50V were recorded.

Figure 5-4: PTO system being tested with utility water

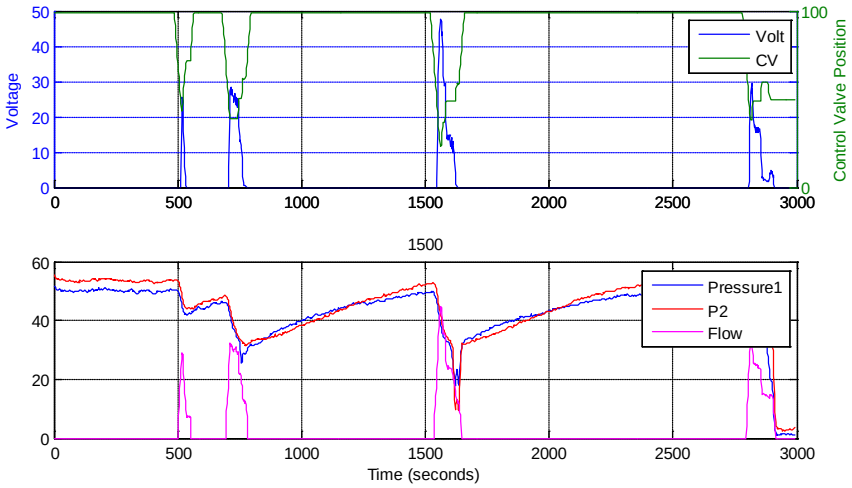


Figure 5-5: Dataset for PTO testing (1)

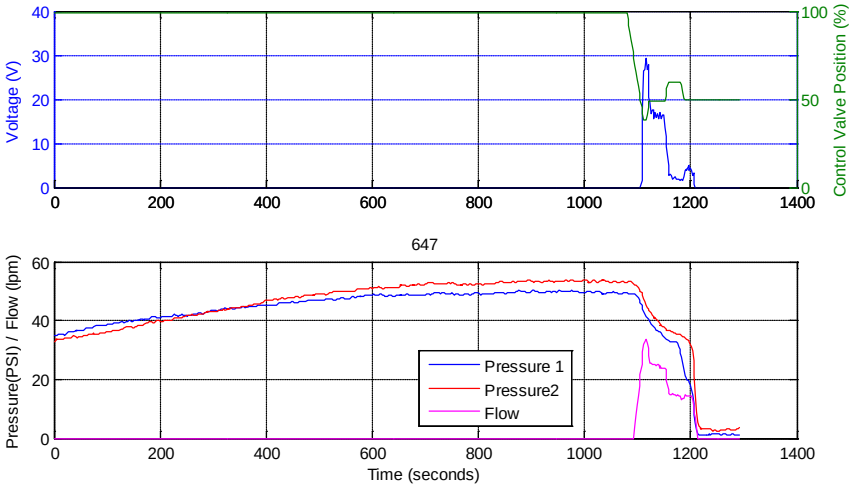


Figure 5-6: Dataset PTO testing (2)

Chapter 6

Deployment

Deploying a full scale system at sea is always a challenge, Ocean forces are often beyond what one expects from lab testing. Ship motion, unexpected current, rogue waves and other factors can take a simple and trivial engineering issue to cause a complete system failure. Ocean deployment for both prototypes was planned to find their performance against real ocean forces. Many interesting lessons were learnt during this experience. This section presents the plan and findings of the deployments in 2012 and 2013.

6.1 Deployment 1 (Summer 2012)

6.1.1 Summary

In the first deployment, both Wing-Wave and GECCO were planned for the testing with PTO. The test site was off the central east coast of Florida, approximately 2.4-km (1.5-mi) east of Ft Pierce Inlet (GPS Coordinates: 27° 26' 0.428" N 80° 13' 0.526" W). The deployment period was June 8-10, 2012. The services of the research vessel M/V

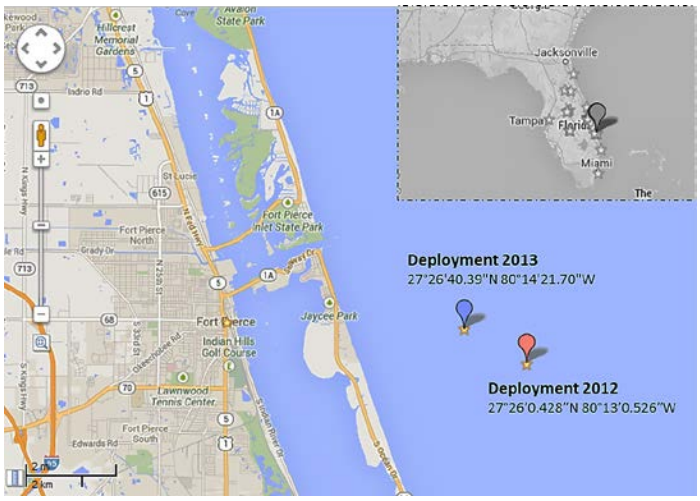


Figure 6-1: Deployment Location

Thunderforce[24], owned by American Vibracore Services, were acquired for the deployment.

The location was near Capron Shoal and NOAA Station 41114[25]. Figure 6-1 shows the deployment location for prototype 1 and 2.

Wing-Wave was deployed on the first deployment day. PTO system had some last minute installations to be completed. So it was deployed on the second day. Both Wing-Wave and PTO were retrieved on the third day of deployment.

6.1.2 Results

Each section of the wave energy system had significant results and many lessons were learned by the design team over the course of the deployment.

The Wing-Wave system was successfully deployed and worked as per design. There was up to ±30 degree pitching movement observed by the flap. There were some minor mechanical fractures in the base, found after retrieval.

GECCO didn't work due to mechanical failure and no data was recorded from the system. It failed due to a water leakage which resulting in the breaking of a connecting rod. The tubes started sinking and were retrieved back after 2 hours of deployment.

There was a high concern regarding the PTO raft's sea-keeping as there wasn't much time left for proper construction before deployment. The PTO raft performed satisfactorily for

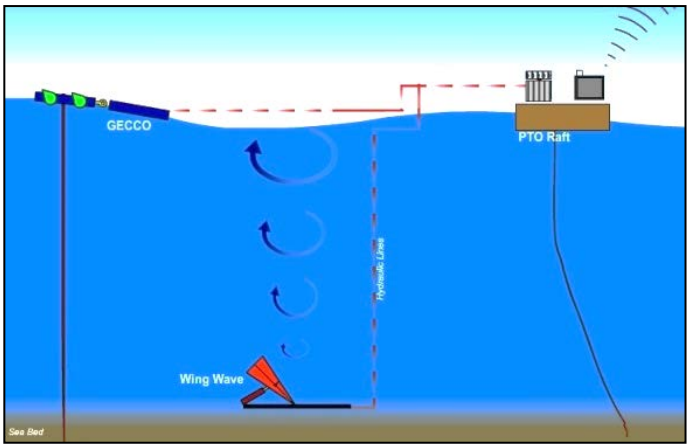


Figure 6-2: Deployment configuration for 2012

[24] Make: 1980; 85 foot steel hull Twin; 10000 lb. stern mounted A-frame crane
[25] NOAA 41114 Buoy; Coordinates: 27°33'5"N 80°13'31"W; Site elevation: sea level; Water depth: 16.15 m

Figure 6-3: PTO raft during deployment

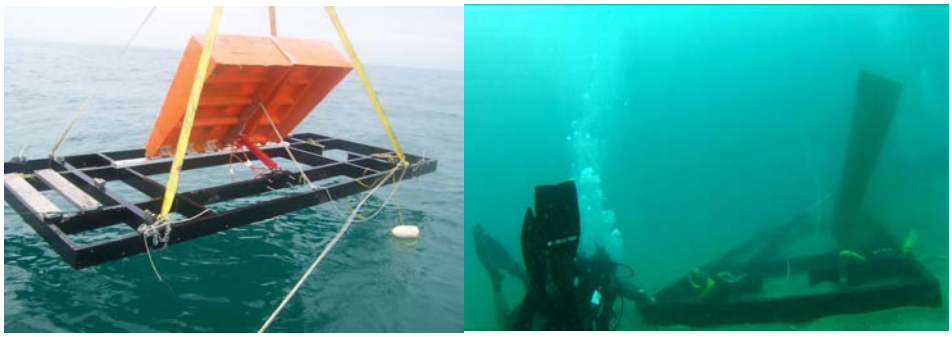


Figure 6-4: Wing-Wave during deployment

the deployment period. However there were issues like stability due to the rectangular design and maintenance provision. The housing of the PTO raft provided sea-worthy protection and there were no water ingress in spite of rough sea state and rains.

The cellular network had good reception throughout the testing. The control system successfully established remote connectivity and logged the instrument data. However, there was a fault in the control algorithm for solenoid valve operation and therefore electrical output could not be generated despite sufficient hydraulic pressure differences generated by the Wing-Wave system. An attempt was made to update the program of the control system, but due to rough seas and limited maintenance access, it was not possible during deployment. Other than this issue, the control system worked as per plan for all the deployment period.

Another problem was the ampere-hour rating of the control supply battery. The control supply died after 36 hours of operation. Battery replacement was tried in PTO raft. However, the ocean waves became high in the afternoon making the PTO raft unstable and dangerous to work on. Due to safety concerns the battery was not replaced.

6.1.3 Weather and Wave data

The sea state and wind state was mainly moderate during the three days of deployment. Swells of period between 6-12 seconds were recorded. Significant wave height observed was between 2-3 feet. Weather was mostly sunny and at times, partially cloudy. Wave rose and period rose[26] for the deployment period are shown in Figure 6-5.

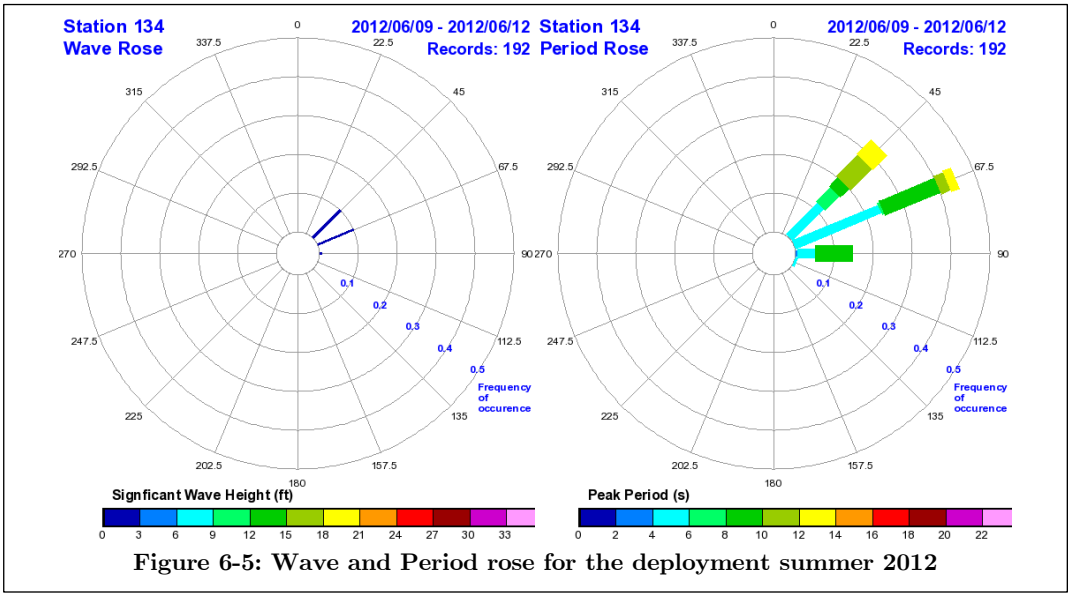


Figure 6-5: Wave and Period rose for the deployment summer 2012

[26] http://cdip.ucsd.edu/?nav=historic&stn=134 & http://www.ndbc.noaa.gov/station_realtime.php?station=41114

6.1.4 Data recorded

As mentioned earlier, due to failure of GECCO and SOV problem with the control system, we were able to record pressure data only from Wing-Wave in deployment. Electricity could not be generated despite strong wave action and ample movement of Wing-Wave flap. Luckily the data acquired was sufficient enough to demonstrate the basic working of the Wing-Wave as per design.

A total of 25 minute worth of healthy data was acquired. Datasets are numbered in the order of their timestamp. Key findings in the datasets are listed below.

#	Dataset No	Duration (s)	Max Value (PSI)	Min Value (PSI)	Comment
1	Dataset 1	575	0	37	
2	Dataset 2	875	5	32	
3	Dataset 3	50	0	32	

Table 6-1: Datasets for deployment 1

Figure 6-6 shows the time series plot for the Wing-Wave pressure recorded.

Data set 1 represents the value when the system was just connected and was starting up. Pressure buildup can be seen in the plot. Dataset 2 and 3 are the samples from the continuous operation of the system. It shows a moving avaerge of 20-25 PSI. The data frequecny is around 6-9 cycles per minute which could be vefied from the video recorded.

Since the PTO was deployed before the hydraulic connections to the Wing-Wave, it was little difficult to exactly pinpoint the root cause. PTO raft didn't have much space for a person to be there during opreration. Apparent reason seems to be either the malfunctioning by SOV or the wrong setpoints for SOV operation. On the basis of lab testing, setpooints of 30 PSI were set. Considering the low flow rate from Wing-Wave, it was later realized that higher setpoints might have been reuired in providing the starting torque to the generator. Additional instrument like flowmeter could have helped to understand the problem during the operation. However there was not much which could be done at that time.

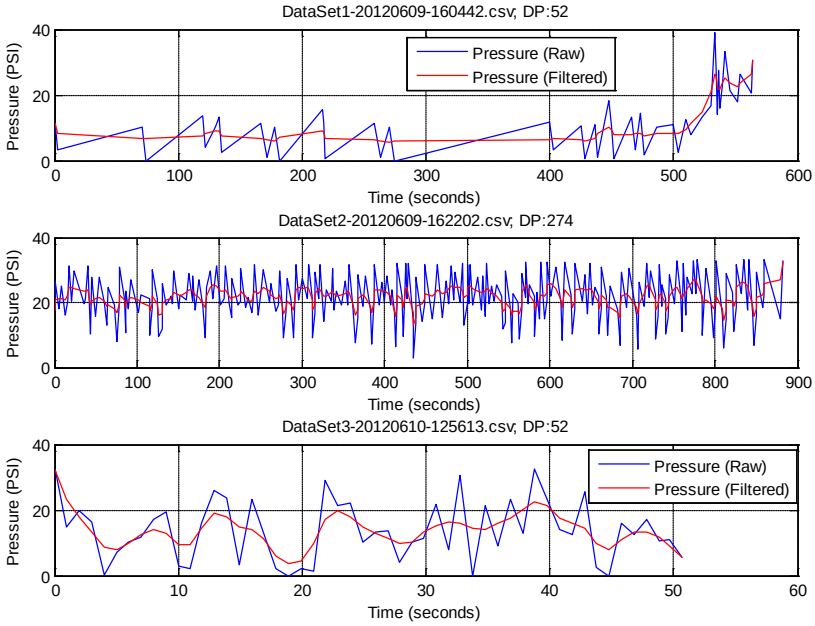


Figure 6-6: Datasets recorded in Deployment 2012

6.2 Deployment 2 (Summer 2013)

6.2.1 Summary

In the first deployment, Wing-Wave and new PTO system were planned for the testing. The test site was near the site for deployment in 2012. GPS Coordinates for the location were 27°26'40.39"N 80°14'21.70"W. The deployment period was June 19-21, 2013. The services of research vessel M/V Richard L. Becker[27], owned by TowBoatU.S., were acquired.

Wing-Wave was deployed on the first day. Keeping in view the experience of last year, it was decided to keep the PTO raft initially on the ship deck and monitor the operation of the control components. On the third day, PTO raft was deployed. On the same day, both units were retrieved after successful demonstration.

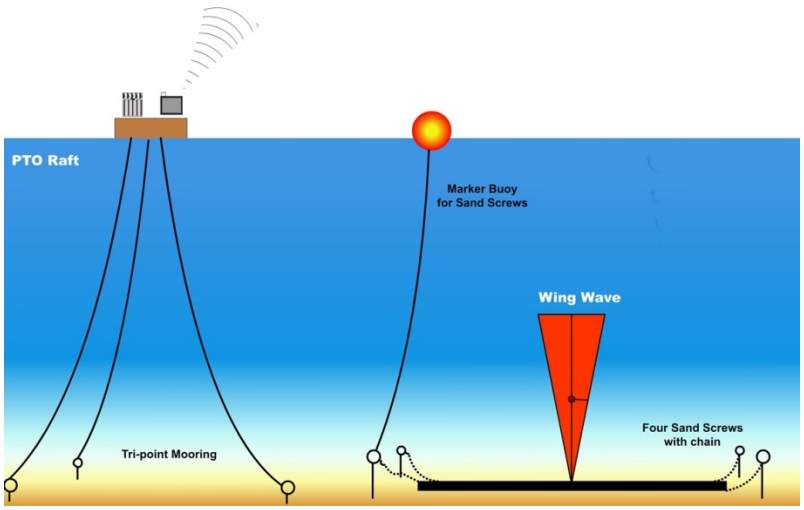


Figure 6-7: Deployment Configuration for 2013

[27] http://www.towboatusftlauderdale.com/Files/Richard_L_Becker_Specs.pdf

6.2.2 Results

Many of the lessons learnt in 2012 deployment were incorporated in the design and construction for second prototype which resulted in overall improved performance especially for the PTO.

However, one unexpected disappointment was the performance of Wing-Wave. One cylinder was added in the system based on the last year's impressive performance of Wing-Wave. The rest of the design was same as last year's. The Wing-Wave was not able to exhibit the pitching movement of more than ± 5 degrees. Movement was in fact at times hardly recognizable. The wave action was pretty much like the waves for 2012. Data from NOAA buoy also supported this observation. Additional oil-filled pressure gauges mounted on the frame of the Wing-Wave helped confirm that the hydraulics were working fine. Different options were tried and eventually one cylinder was removed resulting in a minor improvement to the pitching angle that was sufficient to make the PTO system work. There were no observed mechanical fractures on the structure.

The decision to make the initial tests of PTO and control system on the ship deck proved to be beneficial since it helped to identify the root cause for the slow rate of pressure buildup. All the hydraulics and control system worked as per design. With two pistons connected to flap, the maximum holding pressure stalled at 30 PSI. Triggering attempts for the generator failed at this pressure since the flow rate was already too low. When one cylinder was disconnected, the system pressure went up to 50 PSI. At this pressure, the PTO system was able to provide the minimum starting torque to pelton turbine generator and to rotate it. This was tested several times using the proportional control valves. The generator's no-load output of up to 50V was recorded. Although the generator could not be run for more than 120 seconds due to low flow rate from piston, it was shown that the designed system was able to harness the energy successfully.

All the instrumentation especially the flowmeter worked smoothly. Data was logged locally and transmitted wirelessly by the control system via Xbee modem to the operator station. The remotely sent control commands and set-point assignment were working.

Th hydrodynamic design of the PTO raft seemed to perform better than last year. However, there were some installation issues identified regarding the structural arm connecting main frame with design hull and floatation tubes. Additional straps and securing lines were installed before deployment.

Due to 2012's early discharge of the control system battery, a solar panel was added in the system. The solar panel worked without any issues. There was no low battery condition observed due to this arrangement.

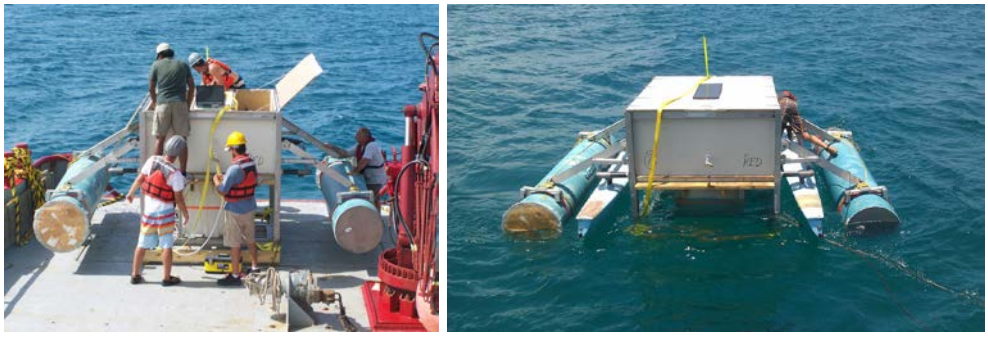


Figure 6-8: PTO raft during deployment

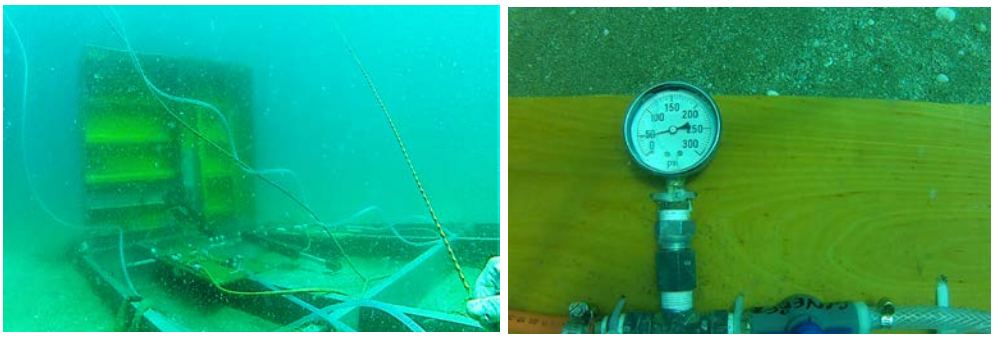


Figure 6-9: Wing-Wave during deployment

6.2.3 Weather and Wave data

Weather and wave data for the second deployment was very much like the 2012 deployment. The sea state and wind state was mainly moderate during the three days of deployment. Swells of period between 8-10 seconds were recorded. Significant wave height observed was between 2-3 feet. Weather was mostlu sunny and at times, partially cloudy. Wave rose and period rose[28] for the deployment period are shown in Figure 6-10.

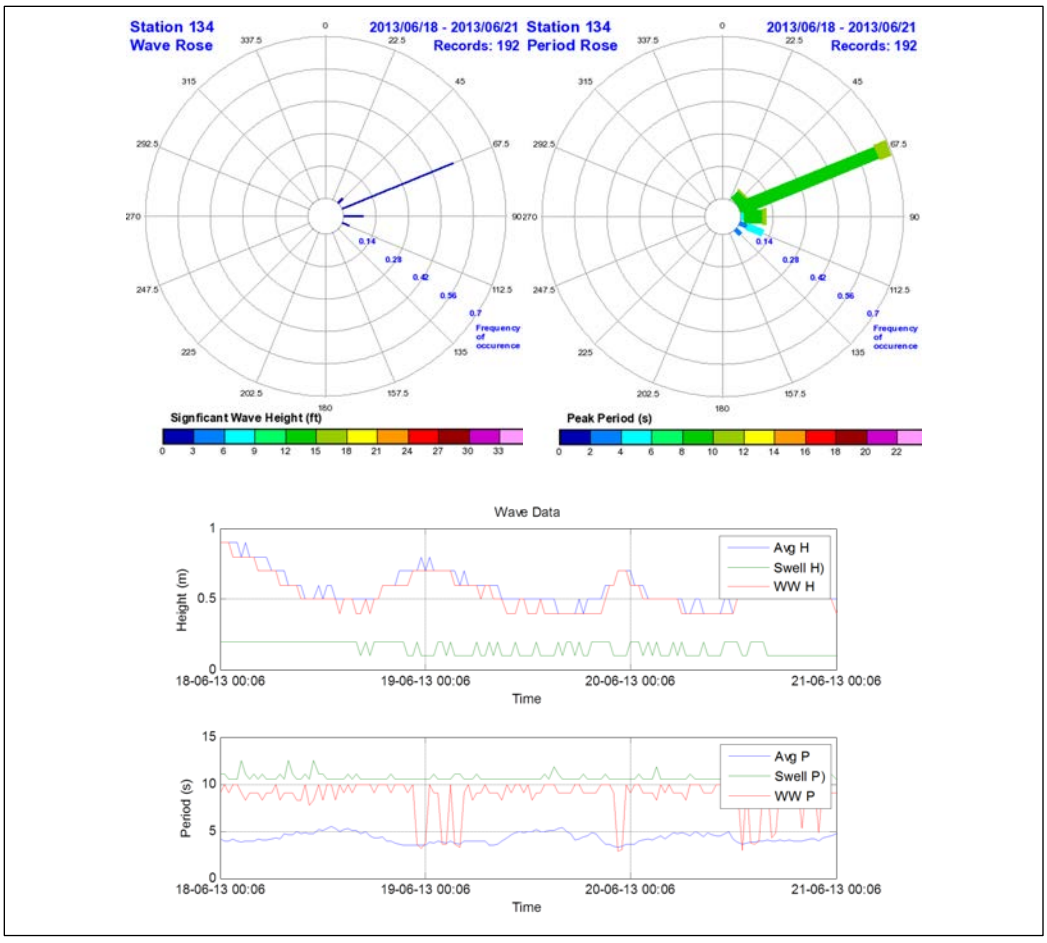


Figure 6-10: (Upper half) Wave and Period Rose for June 2013 (Lower half) Time series plot for Wave Height and period

[28] http://cdip.ucsd.edu/?nav=historic&stn=134 & http://www.ndbc.noaa.gov/station_realtime.php?station=41114

6.2.4 Data Recorded (PTO)

More than 6 hours of PTO data was recorded during deployment. Only selected datasets are shown with commentary in this section. Process variables are shown in two subplots for each dataset. The first subplot includes control valve position (% closure) and Voltage output from generator. Second subplot shows pressure from piston 1, pressure from piston 2 and flow recorded from piston 1. Each dataset is identified by its timestamp.

#	Dataset No	Duration (s)	Comment
1	Dataset 3	500	With two piston
2	Dataset 4	1400	With two piston
3	Dataset 6	1400	With two piston
4	Dataset 7b	5000	Transition from two to one piston
5	Dataset 8	1400	With one piston
6	Dataset 11a	2500	With one piston

Dataset 3, 4 and 6 were recorded with the both pistons connected to Wing-Wave. As can be seen in the plots, the pressure in both hydraulics lines didn't exceed 30 PSI even when it was held for more than 1000 seconds. This 30 PSI was not sufficient to trigger the generator because of the low flow from hydraulic piston.

Dataset 7b shows the transition from two pistons to one piston. As soon as one piston is detached, pressure starts to build up and finally reaches to 50 PSI. Dataset 8 and 11 also show results with one piston. Maximum generator output was recorded up to 50 V whereas maximum flow was recorded up to 60 liter per min. The very low flow rate of hydraulic piston was the reason for the long time taken for the pressure buildup and the small time for generator operation.

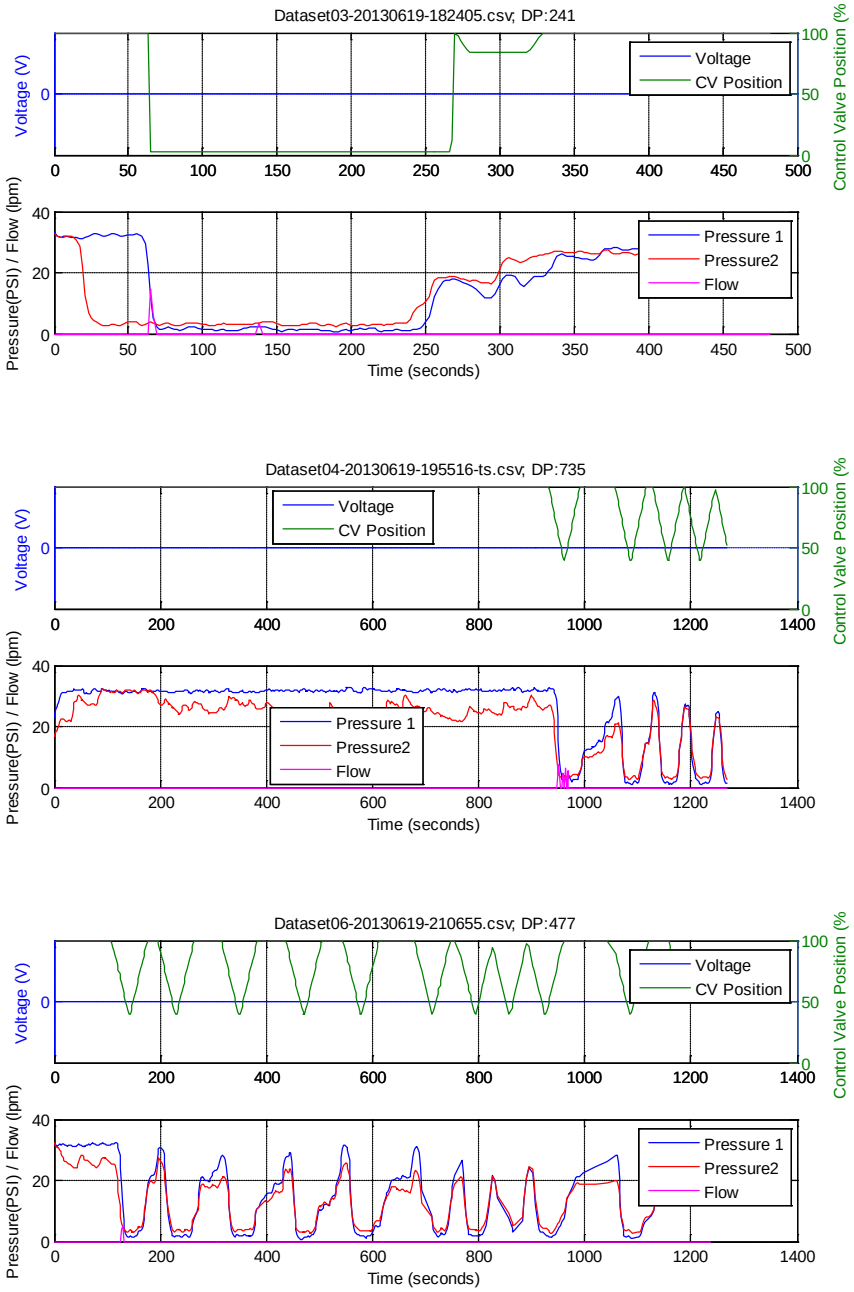


Figure 6-11: Dataset recorded for deployment 2013

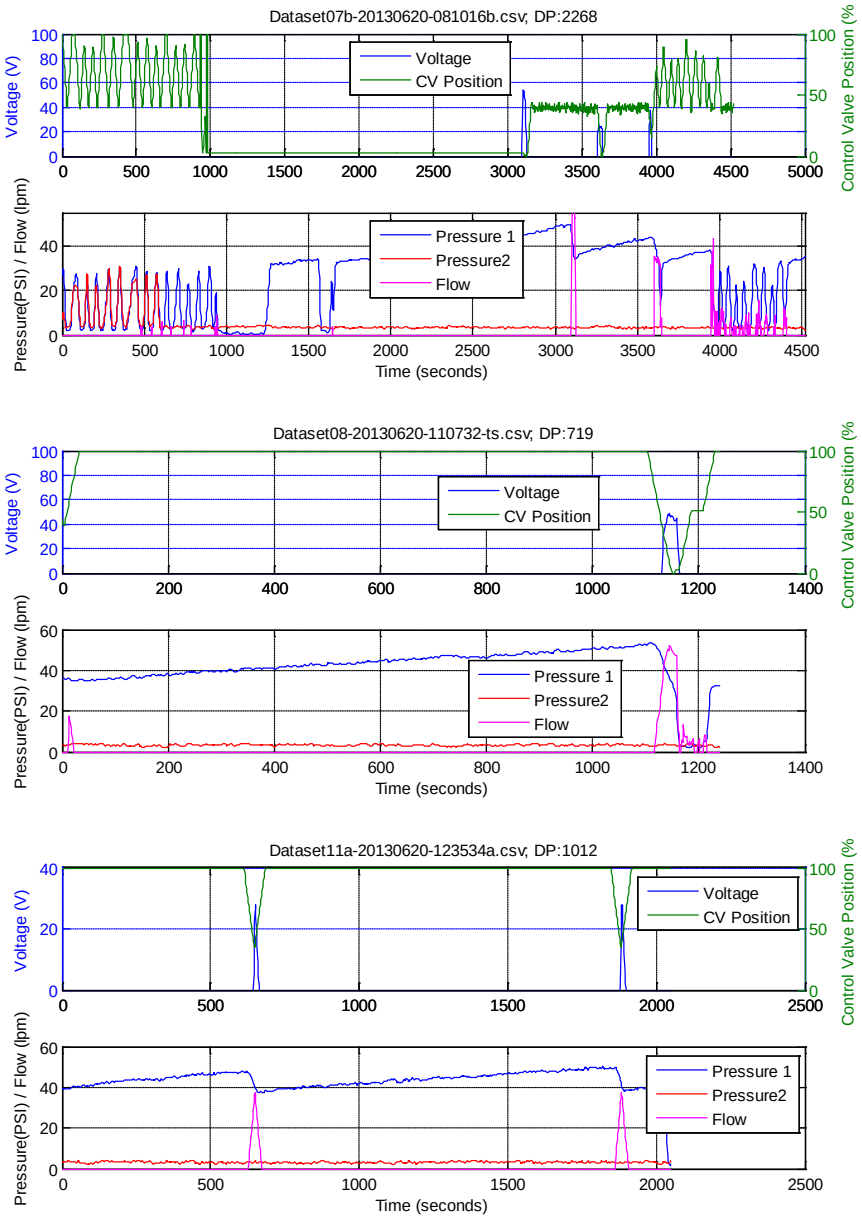


Figure 6-12: Dataset recorded for deployment 2013

6.2.5 Data recorded (Accelerometer)

The data recorded by the accelerometer mounted on the flap of the Wing-Wave confirms the visual observation regarding the flap movement. The plotted data shows that the net pitching movement was around 4 degrees.

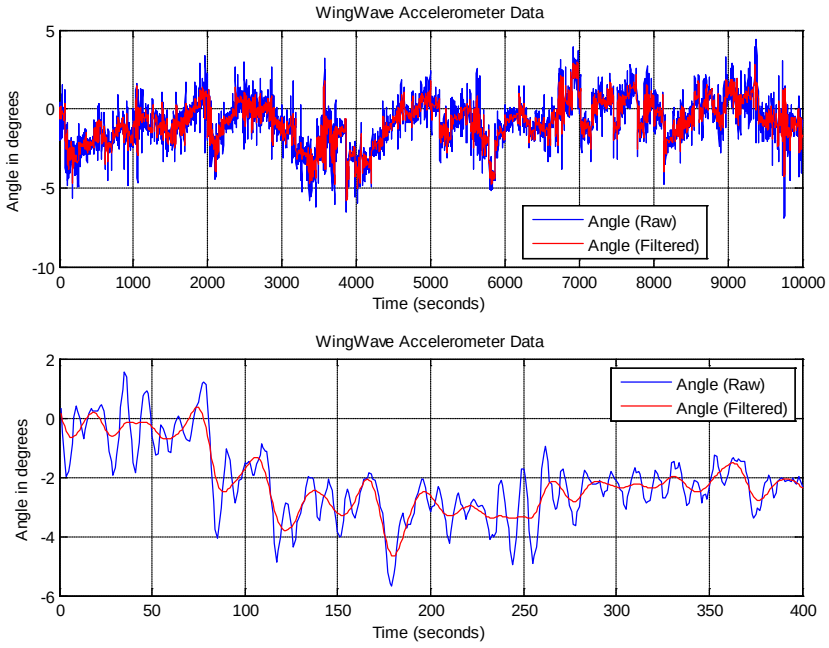


Figure 6-13: Dataset recorded in the deployment 2013

Part IV

Mathematical Modeling

Chapter 7

Mathematical formulation and Validation

This section describes briefly the framework for the mathematical model for flap-type WEC. Modeling marine hydrodynamic problems is not easy due to the real-world limitations complexities and uncertainties. The main focus of this thesis was focused on the actual construction of the power takeoff system. There are numerical tools available for more realistic simulation and modeling of wave forces and behavior of bodies under these forces, however it was not possible to cover them within the time and resources for this thesis.

So in this section, a simple approach is used to estimate the forces and hydraulics of the system to understand the deployment results better. For future teams working on Wing-Wave, this should be a next step to build a more accurate and detailed model since the concept verification has been done for this basic design of WEC and PTO.

The main references used for the formulation of problem are the text from (Renzi and Dias 2012a, 2012b), work done on Wing-Wave in Florida Institute of Technology (Christian et al. 2012) and the book 'Ocean Wave Energy Conversion' (Michael E. McCormick 1981).

7.1 Governing equations for the Flap type WEC

Figure 7-1 presents the flap geometry used by Renzi and Dias (Renzi and Dias 2012a, 2012b). They present a converter having a rectangular flap of width w' and thickness $2a'$, hinged along a straight axis upon a rigid platform, at a distance c' from the bottom of the ocean is placed in water (density ρ) of depth h' in the middle of a straight channel. The channel has impermeable walls placed at a mutual distance b' and extends to infinity to either side.

A plane reference system of coordinates (x', y', z') is defined as following:

- X-axis is on the center line of the channel,
- Y-axis is along the axis of the device at rest position
- Z-axis is vertical to the water surface with $z = 0$ at undisturbed water surface and positive upwards.

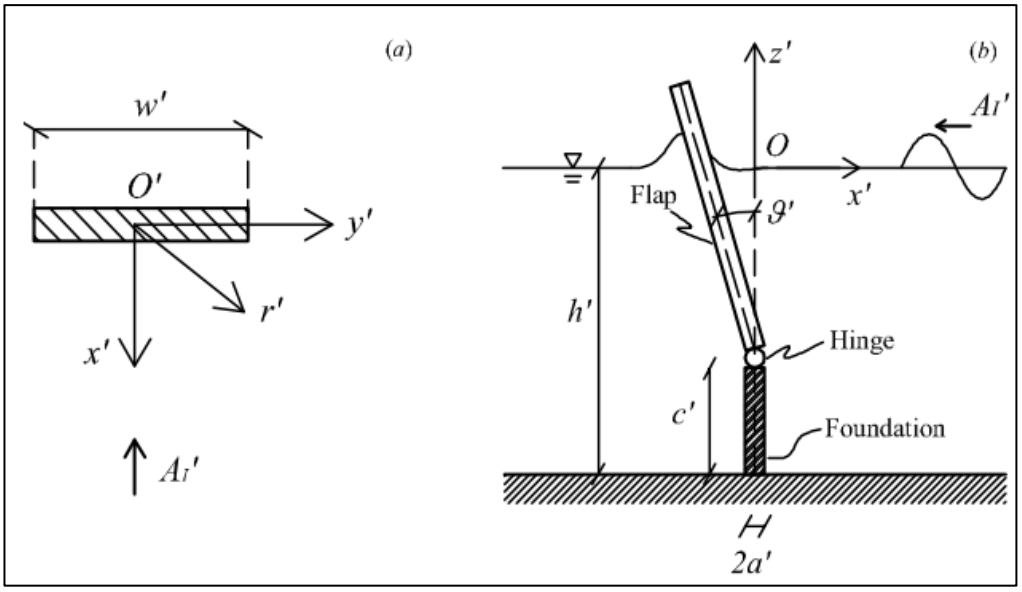


Figure 7-1: Geometry of the Flap type converter (a) section, (b) plan (Renzi and Dias 2012a)

Incident waves (with T wave period and H wave height) are coming from the right with wave crests parallel to the device and set the flap into an oscillating motion. This is eventually converted into useful energy by means of a generator linked to the device.

The flap oscillates on the vertical plane (x′, z′) about the horizontal axis at (x′, z′) = (0, −h′ +c′), and have one degree of freedom, i.e. pitch. Its time-dependent amplitude of rotation ϑ' = $\vartheta'(t')$ is defined positive if counter-clockwise; t′ denotes time.

The fluid is assumed to be non-viscous, incompressible and irrotational. The velocity potential Φ can be defined:

$$\Phi(x,y,z,t) = \Re\{\Phi(x,y,z)e^{-i\omega t}\} \quad 7\text{-}1$$

Laplace Equation where Ω is fluid domain:

$$\nabla^2\Phi = 0\ ;\ (x,y,z) \in \Omega \quad 7\text{-}2$$

To set up a boundary-value problem governing the behavior of the fluid, the Laplace equation must be supplied with appropriate boundary conditions. The kinematic-dynamic boundary condition on the free-surface (with g the acceleration due to the gravity):

$$\frac{\partial^2\Phi}{\partial t^2} + g\frac{\partial\Phi}{\partial z} = 0, z = 0 \quad 7\text{-}3$$

The no-flux conditions on the solid boundaries require on the channel lateral walls

$$\frac{\partial \Phi}{\partial y} = 0, \qquad y = \pm\frac{b}{2} \tag{7-4}$$

And on the bottom:

$$\frac{\partial \Phi}{\partial z} = 0, \qquad z = -h \tag{7-5}$$

A no-flux boundary condition must also be applied on the flap yielding:

$$\frac{\partial \Phi}{\partial x} = 0, \qquad x = \pm a, |y| < \frac{w}{2} \tag{7-6}$$

7.2 Wave Force Calculations on Wing-Wave

7.2.1 Equation of Motion

Eqaution of motion is based on Netwton's second law of motion and represents the forces acting on the body. The equation of motion for wave energy convertor can be shown as (Kamizuru 2010):

$$F_{WEC} = F_{wave} + F_{damping} + F_{spring} + F_{radiation} + F_{loss} \quad 7\text{-}7$$

$$F_{WEC} = m_{WEC}.a$$

Where F_{wave} is the excitation wave force absorbed by the model,
$F_{damping}$ is the mechanical force applied by the hydraulic PTO,
F_{spring} is hydrostatic restoring force due to the buoyancy,
$F_{radiation}$ is associated with the radiation forces caused by the WEC movement,
F_{loss} is the energy loss due to of mechanical and bottom friction, drag, breaking waves etc.
m_{WEC} is mass of WEC, and
a is the acceleration experienced by the WEC

For a bottom hinged plate with 1 degree of freedom (pitching), the equation of motion can be re-written as (Gomes, Lopes, and Henriques 2011):

$$I\ddot{\theta}(t) = M_{wave} + M_{damping} + M_{spring} + M_{radiation} + M_{loss} \quad 7\text{-}8$$

Where, I is the moment of inertia about the pitching axis,
$\ddot{\theta}$ is the instantaneous angular acceleration of the WEC plate and
M represents the corrsponding moment shown in subscript.

To determine these forces and moments accurately, we will have to find several system variables (including radiation coefficient, spring coefficent, damping coeffcient, and frictional losses) which would require additional instruments and numerical analysis (beyond scope of this thesis). A basic analysis for the incident energy calculation is presented in the next section.

7.2.2 Wing-Wave Design and Assumptions

Basis of the wave force calculation in this section is the work on a bottom-mounted flap from book "Ocean Wave Energy Conversion", Section 4.1 E (Michael E. McCormick 1981). To simplify calculations, we will assume forces on a plain flap of dimensions of Wing-Wave in vertical position (x=0). No side or top panel will be considered.

Table 7-1 presents the Wing-Wave variables which will be used in the follwing calculations. We will assume a monochromatic sea with one single wave for the force calculation on the Wing-Wave. Table 7-2 presents the wave data.

From the discussion in Chapter 2, 'Theory' earlier that the water particles in deep water rotate in circular orbits with radius which is exponential function of the depth. In shallow water, these motions become elliptical with almost constant horizontal displacement and decreasing vertical displacement. The flap type WEC oscillates back and forth due to the dynamic pressures induced by the particle motions.

The horizontal motion of the flap is constrained by the pistons attached to the flap. The hydraulic pumping function of the pistons also make them to act like as a damper against the motion of the flap.

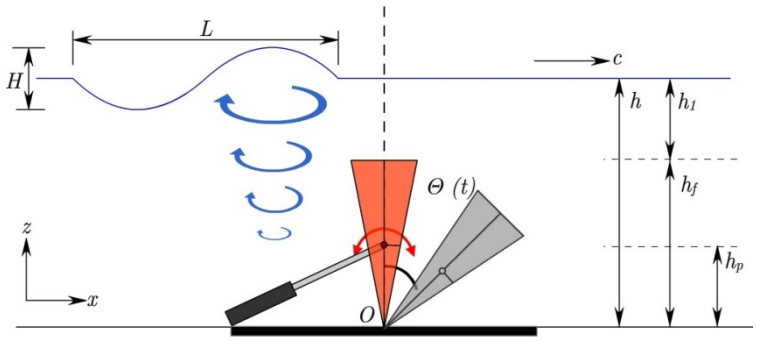


Figure 7-2: Wing-Wave and wave variables

Variable	Name	Value	Unit	Comment
B_f	*Width of Flap*	2.42	m	Two 4 ft wide wings
h_f	*Height of Flap*	1.82	m	6 ft
t_f	*Flap Thickness*	0.01	m	
V_f	*Flap Volume*	0.06	m3	
M_f	*Mass of Flap*	136.36	kg	
ρ_f	*Flap density*	2450.25	kg/m3	
h_p	*Height of Piston Connection*	0.46	m	18 inches
L_f	*Stroke length*	0.61	m	610 mm or 24 inches

Table 7-1: Wing-Wave Design Data

Variable	Name	Value	Unit	Comment
H	*Wave Height*	0.30	m	
L	*Wavelength*	76.80	m	
T	*TimePeriod*	7.92	s	
ρ	*Density*	1025.00	kg/m3	
g	*gravity*	9.80	m/s2	
ν	*Seawater Kinematic Viscosity*	1.05E-06	m2/s	
f	frequency	0.13	Hz	
ω	Angular Frequency	0.79	rad/s	
k	Wave Number	0.08	1/m	
h	*Depth*	10.00	m	
h_1	Distance between top of flap and surface	8.18	m	

Table 7-2: Wave Data

7.2.3 Wave Orbital calculation

The wave induced dynamic pressure is given as:

$$p_d = -\rho \frac{\partial \Phi}{\partial \mathrm{t}} = \frac{\rho g H}{2} e^{kz} cos(\omega t) \quad \text{7-9}$$

The point at which F_f, force due to dynamic pressure, acts on) is at depth:

$$\bar{z}_f = \frac{\int_{-h}^{-h1} p_d \, z \, dz}{\int_{-h}^{-h1} p_d \, dz} = \frac{\int_{-h}^{-h1} e^{kz} z \, dz}{\int_{-h}^{-h1} e^{kz} \, dz} = \frac{e^{kh}(h - h_1)}{e^{kh} - e^{kh_1}} \; - \frac{hk + 1}{k} \quad \text{7-10}$$

$\bar{z}_f = -9.07\mathrm{m}$

This point of force on flap, with respect to the seabed, is at:

$h - \bar{z}_f = 10 - 9.06\, m = \; 0.93\mathrm{m}$

Horizontal Velocity at surface and flap is:

$$u = \frac{gHk}{2\sigma} \frac{\cosh\big(k(h+z)\big)}{\cosh(kh)} \quad \text{7-11}$$

$u|_{z=0} \; = 0.154 \; \frac{m}{s}$; $u|_{z=\bar{z}_f} = 0.114 \frac{\mathrm{m}}{\mathrm{s}} = \; 4.47 \; \frac{\mathrm{inch}}{\mathrm{s}}$;

Vertical Velocity at surface and flap top is:

$$w = \frac{H\sigma}{2} \frac{\sinh\big(k(h+z)\big)}{\sinh(kh)} \quad \text{7-12}$$

$w|_{z=0} = 0.121 \frac{m}{s} \; (at \; z = 0)$; $w|_{z=\bar{z}_f} = 0.01 \frac{m}{s} (at \; z = \bar{z}_f)$

Horizontal Acceleration at surface and flap top is:

$$\frac{Du}{Dt} = \dot{u} = \frac{H}{2} \sigma^2 \frac{\cosh\big(k(h+z)\big)}{sinh(kh)} \sin(\mathrm{kx} - \sigma t) \quad \text{7-13}$$

$\dot{u}|_{z=0} = 0.142 \frac{m}{s^2} \; (at \; z = 0)$; $\dot{u}|_{z=\bar{z}_f} = 0.105 \frac{m}{s^2}$

Vertical Acceleration at surface and flap top is:

$$\frac{Dw}{Dt} = \dot{w} = -\frac{H}{2}\sigma^2 \frac{\sinh\big(k(h+z)\big)}{sinh(kh)}\cos(\mathrm{kx} - \sigma t) \quad 7\text{-}14$$

$$\dot{w}|_{z=0} = -0.096\frac{m}{s};\ \dot{w}|_{z=\bar{z}_f} = 0.008\frac{m}{s}$$

Deep-water displacement at $z = \bar{z}_f$ is:

$$\xi_{DW}|_{z=0} = \frac{H}{2}e^{2kz} = 0.152m \quad 7\text{-}15$$

$$\xi_{DW}|_{z=\bar{z}_f} = \frac{H}{2}e^{2kz} = 0.0344m$$

Horizontal displacement for this depth is (S. M. Folley, Whittaker, and Henry 2007):

$$\xi = \xi_{\mathrm{DW}} \frac{1}{\left(\sqrt{\left(1 + \frac{2kh}{(\sinh(2kh))}\right).\tanh(kh)}\right) \times \tanh(\mathrm{kh})} \quad 7\text{-}16$$

$$\xi|_{z=\bar{z}_f} = 0.0483m$$

7.2.4 Wave Force calculation (McCormick)

The force due to this pressure on flap is:

$$F_f = B_f \int_{-h}^{-h1} p_d = \frac{B_f \rho g H}{2} cos(\omega t)\left(\frac{e^{-kh} - e^{-kh}}{k}\right) \quad 7\text{-}17$$

$$F_f = 3201.85\ \mathrm{N} = 719.80\ \mathrm{lb}$$

Now for the force transmitted to the hydraulic piston, we consider the moment acting on flap at point 'O':

$$F_p h_p = F_f\left(\bar{z}_f\right) \quad 7\text{-}18$$

$$F_p = 6524.30N = 1466.72\ lb$$

The total wave energy transferred to the piston over one wave period is:

$$E_f = \frac{4}{T}\int_0^{T/4} F_p l_f cos(\omega t)\, dt \qquad 7\text{-}19$$

$$E_f \cong l_f \bar{z}_f F_p \times \frac{4}{T}\int_0^{T/4} cos^2(\omega t)\, dt = l_f \bar{z}_f F_p \left(\frac{sin\,(\pi)}{\pi} + \frac{1}{2}\right)$$

$$E_f = \frac{l_f \bar{z}_f F_p}{2} = 909.19\text{J}$$

Power provided to piston over one cycle would be:

$$P = \ P = \frac{E_f}{T} = 114.80\ \frac{J}{s} or\ W \qquad 7\text{-}20$$

For an ideal case, the power that can be extracted from this device in 1 year would be:

$$P_y = 1005.62\ \text{kWh} \qquad 7\text{-}21$$

For the sake of comparison, we will do the power calculations for a small wind turbine (Rosa 2005). The blade diameter D_w is taken as 2.4 m (same as the Wing-Wave's flap width). The rotor swept area for the wind turbine is:

$$A_w = \ \pi\left(\frac{D_w}{2}\right)^2 = \ 4.52\ m^2 \qquad 7\text{-}22$$

At the air speed of 6 $\frac{m}{s}$, the available power in the wind:

$$P_{wind} = \ \rho \times A_w \times \frac{v_a^3}{2} = \ 1.2 \times 4.52 \times \frac{6^3}{2} = \ 585.7\ W \qquad 7\text{-}23$$

The theoretical limit of wind energy that can be transferred to the shaft is 59.26%, known as Betz Limit:

$$P_{Turbine\ Max} = \ P_{wind} \times 0.592 = \ 347.1\ W \qquad 7\text{-}24$$

The typical efficiency of commercially manufactured rotors for residential use is typically 25% to 45%[29]. Considering the efficiency of 30%, extracted power would be:

$$P_{Turbine\ Typ} = \ P_{wind} \times 0.3 = \ 175.7\ W \qquad 7\text{-}25$$

[29] http://windpower.generatorguide.net/wind-energy.html

So a typical wind turbine of same diameter as Wing-Wave flap would generate a theoretical max of 585.7 W and with the efficiency of 30%, approximately 175W.

7.2.5 Capture Width Calculation

Capture width is the indicator of the energy conversion ability of the WEC. It is the ratio of the power absorbed by WEC output and the power per meter of incident wave crest (Price 2009).

The incident power over a unit width of wave front (or energy flux) is given as (Qureshi, Danish, and Khalid 2010):

$$\overline{P_i} = \frac{\rho g H_s^2 T}{64\pi} \cong 0.5 H_s^2 T \ \ \frac{kW}{m} \qquad 7\text{-}26$$

Where $H_s = 1.4\ H_{avg}$ and H_s is the significant wave height.

$$\overline{P_i} = \ 0.717\ \frac{kW}{m} = 717.29\ \frac{W}{m}$$

Capture width ratio for the device, in the given conditions, would be (Price 2009):

$$CW = \frac{P_{abs}}{\overline{P_i}} = \frac{114.80}{717.29}\ \text{m} = 0.16\text{m} \qquad 7\text{-}27$$

$$Relative\ Capture\ Width\ = \frac{CW}{Width\ of Flap} = 6.67\%$$

For the sake of comparison, relative capture width of the commercial flap type devices Oyster and Langlee is between 15-35% (Babarit and Hals 2011).

7.2.6 Surge Wave Force Calculation

The surge force on the body can be estimated as function of body's displaced mass and added mass and water particle acceleration (S. M. Folley, Whittaker, and Henry 2007). So the added mass for the Wing-Wave is (Veritas 2012):

$$m_{add} = \rho 1.51 \pi a^2 = 9606.20 kg \qquad 7\text{-}28$$

'a' is the half of the characteristic length of rectangular body (flap width in this case). So the wave surge force can be shown as:

$$F = (M_v + M_a)\omega^2 \xi = \ 296.23N \qquad 7\text{-}29$$

7.3 Morrison Equation and Force Coefficients

Morison equation is used to evaluate foces acting on body in an oscillatory flow (Havn 2011; Veritas 2012). Morison force is based on two components: Inertia and drag experienced in the flowing fluid. In this section, we will use Morison equation to evaluate the wave forces on the Wing-Wave. We will use the horizontal velocity (eq 7-11) to determine these forces. The total Morrison force is represented as:

$$F_T = F_D + F_i \tag{7-30}$$

Where F_D is the drag force and F_i is the inertia force acting on the body.

The Morrison forces are function of Keulegan–Carpenter number K_c and Reynold Number R_e. Keulegan–Carpenter number K_c for the WingWave is as following (u as the amplitude of the flow velocity oscillation, and D as a characteristic length):

$$K_c = \frac{uT}{D} = 0.37 \tag{7-31}$$

Reynold Number $R_e$is:

$$R_e = \frac{uD}{\upsilon} = 2.63E + 05 \tag{7-32}$$

Slenderness Ratio shows that the Morison Equation is applicable:

$$slenderness\ Ratio = \frac{\pi D}{L} = 0.074 \leq 0.5 \tag{7-33}$$

From Figure 7-3, the drag coefficient C_D and inertial coefficient C_M is found as 0.6 and 1.8 respectively using K_c and R_e values.

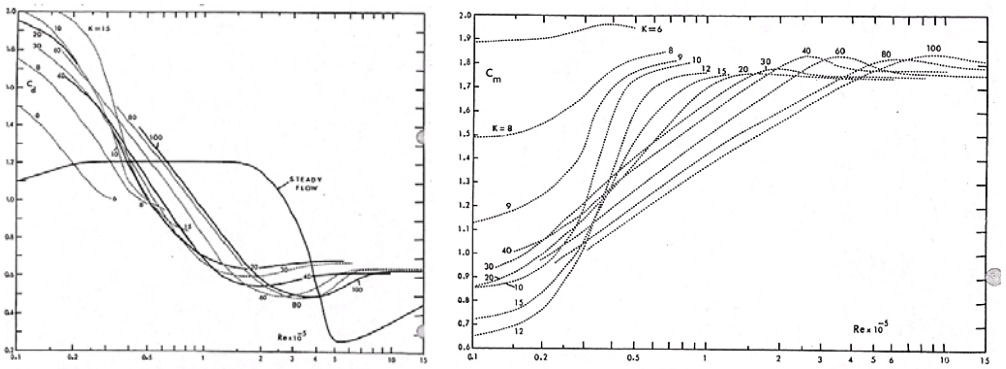


Figure 7-3: (Left) C_D vs R_e for various K_c (Right) C_M vs R_e for various K_c

The horizontal drag force is calculated as:

$$F_D = \frac{1}{2} C_D \rho A \, u \, |u| \qquad \text{7-34}$$

$$F_D = \frac{1}{2} C_D \rho \int_{-h}^{-h1} A \, u \, |u| \; dz = -2616.20N$$

The horizontal inertia force is calculated as:

$$F_i = C_m \rho \, V \frac{Du}{Dt} \qquad \text{7-35}$$

$$F_i = C_m \rho \int_{-h}^{-h1} V \frac{Du}{Dt} \mathrm{dz} = -60.92\mathrm{N}$$

7.4 Force Calculations on Piston

Hydraulic cylinder specifications are as following[30]:

Variable	Name	Value	Unit	Comment
d_1	rod diameter	0.0381	m	1.5"
A_1	rod Area	0.0011	m^2	
d_2	piston diameter	0.0762	m	3"
A_2	piston Area	0.0046	m^2	
l_f	Stroke	0.6096	m	24"
d_n	Nozzle Dia	0.0127	m	Port Size:1/2"
A_n	Nozzle Area	0.0001	m^2	

Table 7-3: Hydraulic Cylinder Data

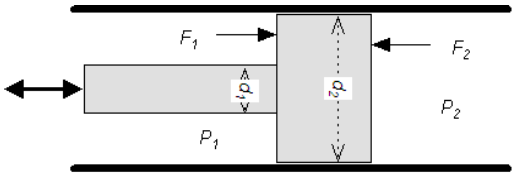


Figure 7-4: Forces acting on the hydraulic cylinder

We have calculated theoretical force on the pistons from Wing-Wave as 6500N. To account for the losses due to real seas issues like different wave incidence angle and mechanical loss for example, we will assume that 20% for the force is actually transferred to the pistons. Also since the practical data suggests that the most of the WEC have conversion efficiency in this range (Babarit and Hals 2011).

So the forces acting on the rod chamber and annular chamber of the piston will be:

$$F_1 = F_2 = 0.2 \times 6524.30\ N = 1360.92N \qquad 7\text{-}36$$

For the given time period, we have following no. of cycles per minute

[30] 30TH24-150 by LION Hydraulics: http://www.monarchindustries.com/lion-hydraulics/tie-rod-cylinders/lion/th/

$$Cycles/min = 7.5949 \quad \text{7-37}$$

We assume that the Wing-Wave oscillates ±10 degrees (i.e. 20 degree or 0.35 rad) about the center position (x=0). So the net distance d_p travelled by the piston in one cycle and corresponding average velocity would be:

$$d_p \cong h_p\theta = 0.46 \times 0.35 = 0.16m \quad \text{7-38}$$

$$v_p = \frac{2d_p}{T} = 0.0403\frac{m}{s}$$

The force on rod side of the cylinder piston is given as:

$$F_1 = \frac{\pi}{4}({d_2}^2 - {d_1}^2)\, p_1 \quad \text{7-39}$$

So the pressure in the cylinder (rod side) would be

$$p_1 = 3.97 \times 10^5 \frac{N}{m^2} = 3.97bar = 57.71\frac{lb}{in^2} \quad \text{7-40}$$

The force on annular side of the cylinder piston and corresponding pressures are:

$$F_2 = \frac{\pi}{4}({d_2}^2)\, p_2 \quad \text{7-41}$$

$$p_2 = 2.98 \times 10^5 \frac{N}{m^2} = 2.98\, bar = 43.28\frac{lb}{in^2}$$

Volume $\mathcal{V}$ of the hydraulic fluid pumped out of cylinder chambers is calculated using

$$\mathcal{V} = Area * stroke \quad \text{7-42}$$

$$\mathcal{V}_1\,(rod) = 0.0005\, m3 = 0.54\, liter = 0.14\, Gal$$

$$\mathcal{V}_2\,(annular) = 0.0007\, m3 = 0.72\, liter = 0.19\, Gal$$

So the discharge from both chambers is connected to one common discharge nozzle through a set of check valves. So total fluid flow per minute from the cylinder in one minute is given as:

$$Q = (V_1 + V_2) * \frac{Cycle}{min} \quad \text{7-43}$$

$$Q = 9.67\ LPM = 2.55\ GPM = 0.16\ LPS = 1.61 \times 10^{-04}\ \frac{m^3}{s}$$

From conservation of mass for incompressible fluid, we know

$$Q = A_1 v_1 = A_2 v_2 = A_n v_n \tag{7-44}$$

So the fluid velocity from discharge nozzle would be:

$$v_1 = 1.26 \frac{m}{s} \tag{7-45}$$

7.5 Hydraulic Work done by the Piston

We will use Bernoulli's Equation in this section to find the hydraulic work (Munson, Young, and Okiishi 2002). Length of rubber hose going from Wing-Wave to PTO raft is 30.3m. Density of the hydraulic fluid (fresh water) is 1000 kg/m^3.

The shaft work head, h_s, is calculated as following using Bernoulli's Equation. The subscript 3 corresponds to the variables at PTO raft end. We will calculate for the PTO end as disconnedted from the circuit to simplify it.

$$\frac{p_1}{\rho g} + \frac{v_1^2}{2g} + z_1 = \frac{p_3}{\rho g} + \frac{v_3^2}{2g} + z_3 + h_s - h_L \tag{7-46}$$

$$\Rightarrow h_{s=} \frac{p_1}{\rho g} + z_1 + (h_{LMajor} + h_{LMinor})$$

So

$$h_{LMinor} = \sum K_{Li} \frac{v_1^2}{2g} = (0.2 \times 2 + 0.05 \times 4) \frac{(1.26^2)}{2 \times 9.8} = 0.049\text{m} \tag{7-47}$$

For h_{LMajor}, we will determine friction factor f using Reynolds Number.

$$R_e = \frac{\rho v D}{\mu} = 9020 \tag{7-48}$$

Since R_e is greater than 1500 threshold so we will use Darcy Weisbach equation for h_{LMajor}. For the rubber hoses, equivalent roughness ϵ is 0.3mm. So $\frac{\epsilon}{D}$ ratio is 0.0236. With calculated values of R_e and $\frac{\epsilon}{D}$, we determine f as 0.05 from (Munson, Young, and Okiishi 2002). Darcy–Weisbach equation yields:

$$h_{LMajor} = f \frac{l}{D} \frac{v_1^2}{2g} = 0.05 \frac{30.3}{0.0127} \frac{(1.26^2)}{2 \times 9.8} = 9.8m \tag{7-49}$$

Shaft work head is calculated as:

$$h_{s=}\frac{p_1}{\rho}+z_1+\left(h_{LMajor}+h_{LMinor}\right) \quad 7\text{-}50$$

$$=\frac{3.97\times10^5}{1000\times9.81}-10+(9.8+0.049)=40.46m$$

So the work done by the hydraulic piston, $\dot{W_{shaft}}$, is:

$$\dot{W_{shaft}}=g\rho Qh_s=9.8\times1000\times1.61\times10^{-04}\times40.46 \quad 7\text{-}51$$

$$\dot{W_{shaft}}=65.53\text{W}$$

So for the given wave conditions, the hydraulic PTO with Wing-Wave can provide up to approx 65W.

7.6 Hydraulics - Accumulators

Accumulators are used in the circuit to dampen the fluctuations and intermittently store the energy in hydraulic form. The data and set-points for the accumulators selected is shown in following table:

	Variables	Value	Unit	Value	Unit
V_T	The total tank volume.	0.136	m^3	36	Gal
P_{1p}	The pre-charge pressure	2.07E+05	Pa	30	PSI
P_{2c}	The cut-in pressure.	1.38E+05	Pa	20	PSI
P_{3c}	The cut-out pressure.	3.45E+05	Pa	50	PSI
P_a	Atmospheric Pressure	1.01E+05	Pa	14.7	PSI

Table 7-4: Hydraulic Accumulator Data

The drawdown calculation, which determines the pressure and volume required, is done in accordance with the Boyle's Law (Wellcare® 2007). For the desired set points, drawdown factor D_f is :

$$DF=\left(\frac{P_{1p}+P_a}{P_{2c}+P_a}-\frac{P_{1p}+P_a}{P_{3c}+P_a}\right) \quad 7\text{-}52$$

$$DF=0.73$$

The total required drawdown, D_T,provided by the accumulator is

$$D_T = V_T \times DF \quad (7\text{-}53)$$

$$D_T = 36\,Gal * 0.73 = 26.28\,Gal$$

The total required drawdown is sum of minimal and supplemental drawdown:

$$D_T = D_{min} + D_{sup} \quad (7\text{-}54)$$

On the basis of the volume of the hydraulic system, we take $D_{min} = 6\,Gal$

$$D_{sup} = (PeakDemand - PumpCapacity) \times [T_{PD}] \quad (7\text{-}55)$$

Where Peak Demand and Pump Capacity are in GPM and $T_{PeakDemand}$ is time for peak demand in minutes. From datasheet of Harris Generator, we take peak demand as 20 GPM for 200W. Pump capacity is taken as 2.5 gal from previous section.

$$26.28 = 6 + (20 - 2.5) * T_{PD} \quad (7\text{-}56)$$

$$T_{PD} = 2.87min = 162\,s$$

At the pumping rate of 2.5 GPM and peak demand of 20 GPM, the selected accumulators will provide the flow for 162 seconds.

7.7 Deployment Result Validation

In this section, a comparison is presented between the measured values in deployment and predicted in this section. It can be seen that for the given conditions and assumptions, the predicted and measured values for the hydraulic PTO system show close match. However, this should be kept in mind that this comparison is only for a reference to understand the deployment results. The predicted values are calculated on the basis of assumptions. The deployment values are the maximum values recorded whereas the predicted values are calculated for flap at x=0 position where forces acting on piston are maximum and 20% efficiency. For the realistic comparison, more instrumentation and detailed model are required.

Hydraulic pressure at cylinder discharge nozzle P_1
Measured Value: $3.30 \times 10^5\ N/m^2$ $49\ PSI$ (Figure 6-12)
Predicted Value: $3.79 \times 10^5\ N/m^2$ $55\ PSI$ (Eq 7-40)

Hydraulic Flow Q
Measured Value: $38\ LPM$ (Figure 6-12)
Predicted Value: $9.67\ LPM$ (Eq 7-43)

Hydraulic Velocity v_1
Observed Value: 1.53 m/s
Predicted Value: 1.26 m/s (Eq 7-45)
Comment: Observed value is based on 12cm vertical height achieved by the hydraulic fluid when PTO hose was disconnected (using Newton's equation of motion, $2gs = v_f^2 - v_i^2$).

Backup Time by Accumulator T_{PD}
Measured Value: 75s (Figure 6-12)
Predicted Value: 162 s (Eq 7-56)
Comment: The observed time backup, as seen in deployment results, is less because the actual flow rate from piston was lower than 2.5 gal used in calculations due to Wing-Wave slow motion.

Part V

Conclusion

Chapter 8

Future Research

This work in this thesis presents the design and development for a prototype WEC. The system was developed to demonstrate a basic working design. There is much room for the improvement and design continuation. This section presents some suggestions regarding the future work for the interested students.

8.1 Simulation and Modeling

The next step for the Wing-Wave should be the development of a complete simulation model that contains all parts needed for optimum energy absorption. For results close to the real world system, this model would need to include mechanics, hydraulics, electrical and control system. Model design approach must consider the real-world criteria.

A good simulation model can be very helpful in efficient and fast system design. A suggestion for the numerical software is Matlab and Simulink (in particulr Simulink Simscape and Real Time Workshop toolbox). One of the reasons for selection of Raspberry Pi as controller was its support in the *real-time workshop* toolbox for Matlab. This means that a control system can be designed in Matlab/Simulink and then can be downloaded in the Raspberry Pi for implementation.

8.2 Hydraulics and Instrumentation

Hydraulic system should be able to handle a wide range of real-sea conditions. Sizing and selection of the hydraulic components should be done keeping in view the system constrains. Simulations can greatly assist in this task.

Integration of additional instrumentation for the wave and power measurement can give valuable information regarding the performance. Standalone wave current meters, force gauges, torque sensor and barometer can be very help in the later analysis. An array of pressure gages can be used to map the dynamic pressure profile on the Wing-Wave, which can be used to find forces acting on the Wing-Wave.

8.3 Wave Tank Testing

If possible, testing of Wing-Wave in a controlled environment will provide a much better opportunity to understand the behaviour of the forces acting on the Wing-Wave. Ocean testing is very tough and often involves many installation and logistic challenges making the full utiliation of the time window hard.

8.4 Power System

In the next phase of work on the Wing-Wave, power system should be upgraded to include more efficient hydraulic generator and single/three-phase convertors. The power system should be capable of working at a range of voltage levels from the wave energy convertor. For the stability and control, a rectifier should be used in first stage for the DC conversion of the electrical output of the WEC and then an IGBT or thyristor based inverter for the regeneration of AC power with the stable frequency and voltage.

Chapter 9

Conclusion

One of the main goals of work in 2012 and 2013 on the Wing-Wave was to design and develop a basic setup for the evaluation of the electrical generating of the device. Concept verification for Wing-Wave design had already been done in 2010 and 2011. The Power Take-off system designed as a part of this thesis work, successfully demonstrated the energy harnessing capabilities of Wing-Wave.

The designed PTO system has all the components required for an effective evaluation of the ocean energy conversion technologies. The hydraulic system gives the flexibility to test the PTO with a wide range of WEC concepts (which converts marine power to linear mechanical excitation). The selection of open-architecture based control components facilitates any future work regarding the control system design. The selected controllers Raspberry Pi and Arduino have support in Matlab and Simulink, which can greatly assist in the efforts for modeling and simulation. The proportional control valves support any implementation of linear control system algorithims. Off-the-shelf instrumentation helps in reliable operation and maintenance. Remote connectivity and Human Machine Interface software ensures easy monitoring and fast troubleshooting of operational issues.

The mathematical work shows that the Wind-Wave design has power potential comparable to a similarly sized typical wind turbine. The hydraulic PTO calculations showed that the power output of approximatley 60W can be achieved with the moderate wave action (provided the Wing-Wave is able to pump the piston smoothly). The calculated maximum hydraulic pressure and velocity were found in accordance with the deployment results. However, this should be kept in mind that the calculations were done with many assumptions regarding the design and input wave conditions. To make the numbers more realistic, numerical modeling and simulations are essential.

Deployment results have greatly helped in building the confidence of the system. Though there were some disappointments, the overall the results were very promising. The operational data acquired helped understand the operation and identify areas for further design improvements. Many of the lessons learned in the 2012 deployment were incorporated in the design and construction for a second prototype which resulted in overall improved performance, especially for the PTO. One interesting improvisation worthy of mentioning

here was the underwater use of oil-filled gauges on Wing-Wave frame. This gave divers ability to verify the Wing-Wave operation underwater and saved time and efforts on troubleshooting. Through a proper design process, including wave tank testing and simulations, the reliability and system performance can be much improved.

Some potential areas of interest for future researchers working on the Wing-Wave are suggested as following:

1. Simulation and modeling of the complete system including real states
2. Design improvements in Wing-Wave for increased capture and better hydrodynamics
3. Hydraulic and mechanical system designing to accommodate a wide range of wave forces
4. Advance power electronics circuitry for integration with power grid
5. Additional instrumentation for the wave and power measurement
6. Design improvements in PTO raft for better sea-keeping and on-site maintenance

To conclude, the power take-off system was able to fulfill its design objectives. Wing-Wave successfully demonstrated the harnessing of the electrical energy from wave power. The system also exhibited the features required for the effective evaluation of ocean energy conversion technologies. This tool can be used for the concept verifications on a small-scale prototype ocean renewable energy technologies developed at Florida Institute of Technology or academic institutions and their later transformation into sea-test scale models.

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Appendix 1: Publications

Paper presented in IEEE Oceans 2012 Conference

Note: Title page only. Complete article can be accessed at:
http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6404951

Development of a Wireless Control and Monitoring System for Wave Energy Converters

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***Abstract*—The Ocean, inherently unstable and uncertain, is one of the harshest environments to test engineering designs; and with the increasing interest in ocean renewable energies, methods and tools must be developed for faster, reliable, low cost, and effective evaluation of the ocean energy technologies. This paper proposes one such tool/system, a small-scale, portable, wireless and universal Power Control and Monitoring Unit (PCMU) for the design and performance evaluation of wave energy converters (WECs). A prototype PCMU system was successfully deployed on June 8th, 2012 with wave energy convertor systems developed at Florida Institute of Technology (Florida Tech).**

***Index Terms*—ocean energy, wave energy, wave energy convertors, wireless, GPRS, power take-off, green energy, alternative energy, renewable energy.**

I. Introduction

The oceans, covering more than 70% of Earth, represent an enormous untapped energy resource containing potentially more energy than the combined output of all other resources on earth. Energy is stored partly in the form of kinetic energy from the motion of waves and currents and partly as thermal energy from the sun. It is estimated that the potential energy of the oceans is up to 2 Million Terawatt-hours [1].

Despite the enormous potential, ocean energy is still an emerging field that is lagging behind the renewable agenda of most countries. Ocean energy technology, being in the experimental and demonstrational phase of development, currently has a high cost for power generation, especially with extreme ocean weather conditions and growing "power-quality" requirements. These and other inherent factors in designing for the ocean create tough engineering problems when balancing efficiency, reliability, and economics with respect to ocean energy systems. The challenges, including the inherent unstable and uncertain nature of ocean energies, management of marine electric grids and stable integration of large amount of renewable energy, have imposed issues in the form of additional system requirements and corresponding costs.

To ensure successful and smooth integration of the oceanic renewable energy generation into large power systems, it is necessary to develop methods and tools for faster, reliable, low cost and effective evaluation of the ocean energy conversion technologies. Such tools can be indispensable for concept verifications on a small-scale (e.g., research and development) and aid in the rapid and successful transformation of ocean renewable energy technologies from prototype to full-scale matured systems.

One aspect of any ocean energy system is to have a reliable, sophisticated and robust controlling mechanism to integrate offshore and onshore power systems [2]. This paper proposes one such tool, a small-scale, portable and universal Power Control and Monitoring Unit (PCMU) for the design and performance evaluation of wave energy converters (WECs).

II. Background

The Ocean Engineering Department at Florida Institute of Technology under the direction of Stephen L. Wood, Ph.D., P.E., has been developing ocean energy systems both above and below the surface since 2007. Currently there are two prototypes WEC's under development at FIT: Wing-Wave, a sea-bed mounted bottom hinged type WEC that captures energy from the horizontal component of wave orbitals at varying depths, and GECCO, a surface floating attenuation WEC for harnessing surface waves.

The Wing-Wave system is designed to capture energy from ocean waves at a depth of 10 to 15 meters and produce electricity. This production of electricity is by harnessing the oscillatory motion of water particles. Particles follow an elliptical path under a shallow water wave. As depth increases the horizontal movement of the particles' rotation remains the same while the vertical movement decreases in shallow water. This causes the motion close to the ocean floor to oscillate in an almost exclusively horizontal direction.

The GECCO (Green Energy Coastal Collection Operation) floats atop the ocean surface and articulates about a fixed hinge and is freely moored to the ocean floor. GECCO uses the Salter Duck technology to capture the rotational motion of the waves. The Salter Duck is a teardrop shaped wave terminator system oriented perpendicular to the direction of the wave with the nose of the teardrop facing the oncoming wave. The device was designed to rotate and "bob" up and down as a wave passes [3]. The bobbing and rotating motion is used to pump hydraulics, which drives an electrical generator. So the GECCO is a floating heave/surge attenuator that works with a combination of a mechanical and a hydraulic system in unison. The GECCO harvests not only the energy of the big swells of the ocean, but the small capillary waves by the addition of Stephen Salters' "Salters Ducks." Different configurations of

Appendix 2: Code

A2.1 Raspberry Pi / Python

```
#!/usr/bin/env python
#
# -----------------------------------------------------------
# Author: Ismail Sultan
# Filename: FinalCodev2.py
# Date: 15-June-2013
# -----------------------------------------------------------

# Constants Definition
import datetime
import time
import os
#import RPi.GPIO as GPIO

#import eeml
#import eeml.datastream
#import eeml.unit
import serial

# -----------------------------------------------------------
# Constants Definition
DEBUG = 1
LOGGER = 1
# -----------------------------------------------------------
## Serial Data log from Arduino

# Initilaize Arduino Serial
port = "/dev/ttyACM0"
serialFromArduino = serial.Serial(port,9600)
serialFromArduino.flushInput()

# Initialize Xbee Serial
serialPortXbee = serial.Serial("/dev/ttyAMA0", 9600, timeout=0.01)
if (serialPortXbee.isOpen() == False):
    serialPortXbee.open()
serialPortXbee.flushInput()
serialPortXbee.flushOutput()

# Initiliaze the file

FilenameInit = (str(datetime.datetime.now()))
FilenameInit = FilenameInit[:FilenameInit.find(".")]
FilenameInit = FilenameInit.replace(":","")
FilenameInit = FilenameInit.replace("-","")
FilenameInit = FilenameInit.replace(" ","-")
filename = FilenameInit + (".txt")
DataLogFile = open( filename, 'w')

DataLogFile.write("Date&Time"+'\t'+"P1"+'\t'+"P2"'\t'+"GV"+'\t'+"Current"+'\t'+"Temp"+'\t'+"B12V"+'\t'+"B24V
"+'\t'+"CVFB1"+'\t'+"CVFB2"+'\t'+"CV_CMD1"+'\t'+"CV_CMD2"+'\t'+"FlowVol"+'\t'+"FlowLPM"+'\t'+"FlowLPH"+'\t'+
"Mode"+'\r'+'\n')

# -----------------------------------------------------------
```

```
# MAIN LOOP
# Serial Data log from Arduino

while True:
    readingsRAW = serialFromArduino.readline()
    print readingsRAW
    print readingsRAW.find("P1")

    #if (readingsRAW[1:2] == "P"):
    # Check if data is healthy ??
    if (readingsRAW.find("P1") == 0):

        readings = readingsRAW.strip().split(' ')     # the readings are separated by spaces

        if (len(readings) == 17): # No missing packets



            # Store in Variables, Remove Text characters
            #= Convert.ToSingle(TestArray1(0).Substring(TestArray1(0).IndexOf("=") + 1))

            Pressure1 = readings[ 0 ][readings[ 0 ].find("=")+1:len(readings[ 0 ])]
            Pressure2 = readings[ 1 ][readings[ 1 ].find("=")+1:len(readings[ 1 ])]
            Pressure1SP = readings[ 2 ][readings[ 2 ].find("=")+1:len(readings[ 2 ])]
            Pressure1SP = readings[ 3 ][readings[ 3 ].find("=")+1:len(readings[ 3 ])]
            Voltage = readings[ 4 ][readings[ 4 ].find("=")+1:len(readings[ 4 ])]
            Current = readings[ 5 ][readings[ 5 ].find("=")+1:len(readings[ 5 ])]
            Temperature = readings[ 6 ][readings[ 6 ].find("=")+1:len(readings[ 6 ])]
            Bat12V = readings[ 7 ][readings[ 7 ].find("=")+1:len(readings[ 7 ])]
            Bat24V = readings[ 8 ][readings[ 8 ].find("=")+1:len(readings[ 8 ])]
            CVFB1 = readings[ 9 ][readings[ 9 ].find("=")+1:len(readings[ 9 ])]
            CVFB2 = readings[ 10 ][readings[ 10 ].find("=")+1:len(readings[ 10 ])]
            CVCmd1 = readings[ 11 ][readings[ 11 ].find("=")+1:len(readings[ 11 ])]
            CVCmd2 = readings[ 12 ][readings[ 12 ].find("=")+1:len(readings[ 12 ])]
            Flow_Total  = readings[ 13 ][readings[ 13 ].find("=")+1:len(readings[ 13 ])]
            Flow_LPM  = readings[ 14 ][readings[ 14 ].find("=")+1:len(readings[ 14 ])]
            Flow_LPH = readings[ 15 ][readings[ 15 ].find("=")+1:len(readings[ 15 ])]
            Opmode = readings[ 16 ][readings[ 16 ].find("=")+1:len(readings[ 16 ])]

            # -------------------------------------------------------------
            # Send Data to Xbee
            serialPortXbee.write(readingsRAW)

            # -------------------------------------------------------------
            #  FILE OPERATION

DataLogFile.write(str(datetime.datetime.now())+'\t'+Pressure1+'\t'+Pressure2+'\t'+Pressure1SP+'\t'+Pressure1
SP+'\t'+Voltage+'\t'+Current+'\t'+Temperature+'\t'+Bat12V+'\t'+Bat24V+'\t'+CVFB1+'\t'+CVFB2+'\t'+CVCmd1+'\t'
+CVCmd2+'\t'+Flow_Total+'\t'+Flow_LPM+'\t'+Flow_LPH+'\t'+Opmode+'\r'+'\n')
            # -------------------------------------------------------------
            # Send it to COSM on internet

              API_KEY = 'P5cAFABVXlV7g5LARDqXMQqbJXeq8oTuUwN9iKzs8dqVNEs1'
            FEED = 1480855249

            API_URL = '/v2/feeds/{feednum}.xml' .format(feednum = FEED)

            if LOGGER:
                # open up your cosm feed
                pac = eeml.Pachube(API_URL, API_KEY)

                # Data
                pac.update([eeml.Data("Pressure1",Pressure1, unit=eeml.Unit('PSI','derivedSI','PSI'))])
                pac.update([eeml.Data("Pressure2",Pressure2, unit=eeml.Unit('PSI','derivedSI','PSI'))])
                pac.update([eeml.Data("Voltage",Voltage,unit=eeml. Unit('Volt','derivedSI','V'))])
```

```
            pac.update([eeml.Data("Current",Current,unit=eeml.Unit('Ampere','basicSI','A'))])
            pac.update([eeml.Data("Bat12V",Bat12V,unit=eeml.Unit('Volt','derivedSI','V'))])
            pac.update([eeml.Data("CVFB1",CVFB1,unit=eeml.Unit('Percentage','derivedSI','%'))])
            pac.update([eeml.Data("CVFB2",CVFB2,unit=eeml.Unit('Percentage','derivedSI','%'))])
            pac.update([eeml.Data("Flow_Total",Flow_Total,unit=eeml.Unit('Liters','derivedSI','l'))])

      pac.update([eeml.Data("Flow_LPM",Flow_LPM,unit=eeml.Unit('Literspermin','derivedSI','lpm'))])
      pac.update([eeml.Data("Opmode",Opmode,unit=eeml.Unit('Mode','derivedSI','Mode'))])


            # send data to cosm
            pac.put()

            # hang out and do nothing for 10 seconds, avoid flooding cosm
            #time.sleep(1)

# This portins takes serial command from Xbee and transfer those to the Arduino

readingsXbee = serialPortXbee.readline()
if  (len(readingsXbee) > 0):

    readingsXbeePackets = readingsXbee.strip().split(' ')     # Split Xbee packets to check them
    #serialPortXbee.write("AAAAAA")
    #serialPortXbee.write(len(readingsXbee))
    if (len(readingsXbeePackets) == 5):
        # Write Xbee commands to the Arduino
        serialFromArduino.write(readingsXbee)
```

A2.2 Arduino

Note: Code for Arduino

```
# ------------------------------------------------------------
# Author: Ismail Sultan
# Filename: WingWaveTestv5_2.ino
# Date: 15-June-2013
# ------------------------------------------------------------

//~~~
```

```
boolean step1 = true;
boolean step2 = false;
boolean step3 = false;


int       PressureSensor1_Raw =         0;        //
int       PressureSensor2_Raw =         0;        //
int       GenVoltage_Raw          =     0;        //
int       Load_Current_Raw    =         0;        //
int       Temperature_Raw             = 0;        //
int       Battery12V_Raw              = 0;        //
int       Battery24V_Raw              = 0;        //
int       ControlValveFB1_Raw =         0;        //
int       ControlValveFB2_Raw =         0;        //

double    PressureSensor1_Mapped        =         0;        //
double    PressureSensor2_Mapped        =         0;        //
double    GenVoltage_Mapped   =         0;        //
double    Load_Current_Mapped =         0;        //
double    Temperature_Mapped  =         0;        //
float     Battery12V_Mapped   =         0;        //
double    Battery24V_Mapped   =         0;        //
double    ControlValveFB1_Mapped        =         0;        //
double    ControlValveFB2_Mapped        =         0;        //

double ControlValve1_Cmd_Map = 0;      // % Open Command; For reference only
double ControlValve2_Cmd_Map = 0;      // % Open Command; For reference only

//~~~
```

```
                    input_stringcomplete = true;
                    inputstring.trim();
                    inputstringFinal = inputstring;

                    // sensorstringFinal.replace("," , " ");
                    // sensorstringFinal.trim();

                    PressureSetpoint1  = (int) (getValue(inputstringFinal, ' ', 0));
                    PressureSetpoint2 = (int) (getValue(inputstringFinal, ' ', 1));

                    ControlValve1_Command100  = (int) (getValue(inputstringFinal, ' ', 2));
                    ControlValve2_Command100  = (int) (getValue(inputstringFinal, ' ', 3));

                    OperationMode      = (int) (getValue(inputstringFinal, ' ', 4));

                    ControlValve1_Command100=constrain(ControlValve1_Command100, 16, 100);
                    ControlValve2_Command100=constrain(ControlValve2_Command100, 16, 100);

                    PressureSetpoint1=constrain(PressureSetpoint1, 5, 200); // Change from 25-100 t o5-200
                    PressureSetpoint2=constrain(PressureSetpoint2, 5, 200);

                    OperationMode      = constrain(OperationMode, 0, 1);

                    ControlValve1_Command = map(ControlValve1_Command100, 0, 100, 0, 255);
                    ControlValve2_Command = map(ControlValve2_Command100, 0, 100, 0, 255);

                    // Serial.print("Done" );
                    inputstring ="";

                }               //if the incoming character is a <CR>, set the flag
            }

//

//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
// Serial Port 2 - From Flow Sensor
// This will built the complete string : Total_Volume, LPM, LPH,

void serialEvent2(){                                //if the hardware serial port_2 receives a char
            char inchar2 = (char)Serial2.read();      //get the char we just received
            sensorstring += inchar2;                  //add it to the inputString
            if(inchar2 == '\r') {
                    sensor_stringcomplete = true;
                    sensorstringFinal = sensorstring;

                    sensorstringFinal.replace("," , " ");
                    sensorstringFinal.trim();

                    Flow_Total = getValue(sensorstringFinal, ' ', 0);  //float f = atof(carray)
                    Flow_LPM   = getValue(sensorstringFinal, ' ', 1);
                    Flow_LPH   = getValue(sensorstringFinal, ' ', 2);

                    sensorstring = "";               //clear the string:
                    //Serial.print (Flow_Total);

                }               //if the incoming character is a <CR>, set the flag
            }

//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

 float getValue(String data, char separator, int index)
{
  int found = 0;
  int strIndex[] = {0, -1};
  int maxIndex = data.length()-1;
```

```
  String finalstring;
  float finalfloat;

  for(int i=0; i<=maxIndex && found<=index; i++){
    if(data.charAt(i)==separator || i==maxIndex){
        found++;
        strIndex[0] = strIndex[1]+1;
        strIndex[1] = (i == maxIndex) ? i+1 : i;
    }
  }

  finalstring = found>index ? data.substring(strIndex[0], strIndex[1]) : "";

  char carray[finalstring.length() + 1]; //determine size of the array
http://forum.arduino.cc/index.php/topic,45357.0.html
  finalstring.toCharArray(carray, sizeof(carray)); //put readStringinto an array
  finalfloat = atof(carray);

  return finalfloat;
}

//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

float mapfloat(float x, float in_min, float in_max, float out_min, float out_max)
{
  return (x - in_min) * (out_max - out_min) / (in_max - in_min) + out_min;
}

//~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
void loop() {

  // ~~~~~~~~~~~~~~~~~~~~
  // STEP # 1
  // Read the analog values:

  PressureSensor1_Raw = analogRead(PressureSensor1);
  PressureSensor1_Mapped = mapfloat(PressureSensor1_Raw, 190, 1023, 0, 200);
  delay(1);

  // Pressure error handling
  //

  PressureSensor2_Raw  = analogRead(PressureSensor2);
  PressureSensor2_Mapped  = mapfloat(PressureSensor2_Raw, 190, 1023, 0, 200);
  delay(1);
  GenVoltage_Raw  = analogRead(GenVoltage);
  GenVoltage_Mapped  = mapfloat(GenVoltage_Raw, 0, 1023, 0, 65.97560);  // 8.2k/(100k+8.2k)
  delay(1);

  Load_Current_Raw  = analogRead(Load_Current);
  Load_Current_Mapped = mapfloat(Load_Current_Raw, 0, 1023, 0, 5); // 5 Amperes
  delay(1);

  Temperature_Raw  = analogRead(Temperature);
  Temperature_Mapped = map(Temperature_Raw, 0, 1023, 0, 100);
  delay(1);

  Battery12V_Raw  = analogRead(Battery12V);
  Battery12V_Mapped  = mapfloat(Battery12V_Raw, 0, 1023, 0, 13.484); // 33k/(56+33)k

  delay(1);

  Battery24V_Raw  = analogRead(Battery24V);
  Battery24V_Mapped  = mapfloat(Battery24V_Raw, 0, 1023, 0, 27.727272);  //22k/(22+100)k
  delay(1);
```

```
  ControlValveFB1_Raw  = analogRead(ControlValveFB1);                  // Mapped to %close
  ControlValveFB1_Mapped  = mapfloat(ControlValveFB1_Raw, 0, 1023, 0, 107);  // 47/(47+47)
  delay(1);
  ControlValveFB2_Raw  = analogRead(ControlValveFB2);
  ControlValveFB2_Mapped  = mapfloat(ControlValveFB2_Raw, 0, 1023, 0, 107);   // 47/(47+47)
  delay(1);

  // ~~~~~~~~~~~~~~~~~~~~
  // STEP # 2
  //
  // If pressure is greater than 50 PSI (or PressureSetpoint1) then Open the Valves (relays activated)

           if (OperationMode == 0){ // Auto

                if ((PressureSensor1_Mapped>PressureSetpoint1) && (step1==true) && (step2==false) &&
(step3==false)) {
                  //digitalWrite(Relay_CloseCV1, CVState_ForceOpen);

                  ControlValve1_Command = 90;   //(0% close of full open)  26% .
                                                //should be good to start this again.

                  //analogWrite(ControlValve1_PWM, ControlValve1_Command);
                  ControlValve2_Command = 90; //
                  //analogWrite(ControlValve1_PWM, ControlValve1_Command);
                  step1=false;
                  step2=true ;
                  step3=false;
                }
               else  if ((GenVoltage_Mapped>15 ) && (step1==false) && (step2==true) && (step3==false) &&
(ControlValveFB1_Mapped <40)) {

                 ControlValve1_Command = 179; // back to 70% to save energy
                 ControlValve2_Command = 179; //
                  step1=false;
                  step2=false ;
                  step3=true;
               }

                else  if ((GenVoltage_Mapped<13 ) && (step1==false) && (step2==false) && (step3==true)) {

                 ControlValve1_Command = 255; // full close since voltage dropped
                 ControlValve2_Command = 255; // BACK to step1
                 step1=true;
                 step2=false ;
                 step3=false;


               }
           }

  else if (OperationMode == 1) // Manual
  {
       // Nothing.
        step1=true; // so if auto loop is broke
        step2=false ;

  }

   // Update PWM Values
  analogWrite(ControlValve1_PWM, ControlValve1_Command);   // analogRead values go from 0 to 1023,
                                                           //analogWrite values from 0 to 255
  analogWrite(ControlValve2_PWM, ControlValve2_Command);   //

  ControlValve1_Cmd_Map = map(ControlValve1_Command, 0, 255, 0, 100);
  ControlValve2_Cmd_Map = map(ControlValve2_Command, 0, 255, 0, 100);
```

```
 // Update Relay Status ======================
 if (ControlValve1_Command <= 40)
       digitalWrite(Relay_CloseCV1, CVState_ForceOpen);
 else
       digitalWrite(Relay_CloseCV1, CVState_AnalogOperation);

 if (ControlValve2_Command  <= 40)  // >= 214
       digitalWrite(Relay_CloseCV2, CVState_ForceOpen);
 else
       digitalWrite(Relay_CloseCV2, CVState_AnalogOperation);

 // Serial Print
 // This will be done with the flowmeter reading
 // Send all values on the Serial to Raspberry Pi

if (sensor_stringcomplete){           //if a string from the Atlas Scientific product
                                      //has been recived in its entierty
     Serial.print("P1=" );                      // "\t; "
     Serial.print(PressureSensor1_Mapped);
     Serial.print(" P2=");
     Serial.print(PressureSensor2_Mapped);
     Serial.print(" P_S1=");                    // "\t; "
     Serial.print(PressureSetpoint1);
     Serial.print(" P_S2=" );
     Serial.print(PressureSetpoint2);

     Serial.print(" GV=" );
     Serial.print(GenVoltage_Mapped,4);      //       Serial.print(GenVoltage_Mapped, 4);
     Serial.print(" Cur=" );
     Serial.print(Load_Current_Mapped);
     Serial.print(" T=" );
     Serial.print(Temperature_Mapped);

     //Serial.print(" Vcc=" );
     //Serial.print(Vcc_5V, DEC);

     Serial.print(" B12V=" );
     Serial.print(Battery12V_Mapped, 4);
     Serial.print(" B24V=" );
     Serial.print(Battery24V_Mapped, 4);
     Serial.print(" CVFB1=" );
     Serial.print(ControlValveFB1_Mapped);
     Serial.print(" CVFB2=" );
     Serial.print(ControlValveFB2_Mapped);

     Serial.print(" CV_CMD1=" );
     Serial.print(ControlValve1_Command100);
     //Serial.print(ControlValve1_Command);
     Serial.print(" CV_CMD2=" );
     Serial.print(ControlValve2_Command100);
    // Serial.print(ControlValve2_Command);

    Serial.print(" FT=" );
    Serial.print(Flow_Total,4) ;
    Serial.print(" FLPM=" );
    Serial.print(Flow_LPM,4) ;
    Serial.print(" FLPH=" );
    Serial.print(Flow_LPH,3)  ;
    Serial.print(" Mode=" );
    Serial.print(OperationMode)  ;


    Serial.write('\r');    // Carriage Return Character ASCII 13
    Serial.write('\n');    // Line Feed Char, ASCII 10
```

```
    sensor_stringcomplete = false;    //reset the flage used to tell if we have recived
                                      //a completed string from the Atlas Scientific product
     }


  // wait 2 milliseconds before the next loop
  // for the analog-to-digital converter to settle after the last reading:
  delay(2);
}
```

A2.3 Visual Basic

Note: Code for Human Machine Interface

```
' -------------------------------------------------------------
' Author: Ismail Sultan
' Filename: FormWingWave_v1_5.vb
' Date: 15-June-2013
' -------------------------------------------------------------

Imports System
Imports System.ComponentModel
Imports System.Threading
Imports System.IO.Ports

Public Class frmMain

    Dim myPort As Array  'COM Ports detected on the system will be stored here
    Dim returnStr As String = ""
    Delegate Sub SetTextCallback(ByVal [text] As String)   'Added to prevent threading
                                                           'errors during receiveing of data

    Dim GoodPacket As Long = 0
    Dim BadPacket As Long = 0.0

    Dim a As String
    Dim InputDataSet As String

    Dim tDate As New DateTime(Date.Today.Year, Date.Today.Month, _
                              Date.Today.Day, Date.Now.Hour, Date.Now.Minute, Date.Now.Second)
    Dim csvFile As String = "C:\TestData\" & tDate.ToString("yyyyMMdd_HHmmss") & ".txt"
    'Dim FILE_NAME As String = "C:\TestData\test.txt"
    Public objWriter As New System.IO.StreamWriter(csvFile, True)

    Structure DataSetWingWave 'Create a structure
        Public Pressure1 As Single
        Public Pressure2 As Single
        Public Pressure1SP As Single
        Public Pressure2SP As Single

        Public Voltage As Single
        Public Current As Single

        Public Temperature As Single

        Public Bat12V As Single
        Public Bat24V As Single

        Public CVFB1 As Single
        Public CVFB2 As Single
        Public CVCmd1 As Integer
        Public CVCmd2 As Integer

        Public Flow_Total As Single
        Public Flow_LPM As Single
        Public Flow_LPH As Single

        Public OpMode As Single

    End Structure

    Dim Data1 As DataSetWingWave
```

```
    Private Sub frmMain_FormClosing(ByVal sender As Object, _
                            ByVal e As System.Windows.Forms.FormClosingEventArgs) Handles Me.FormClosing
        objWriter.Close()
    End Sub

    '~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    '   Initialization
    '
    '~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    Private Sub frmMain_Load(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles MyBase.Load

        myPort = IO.Ports.SerialPort.GetPortNames() 'Get all com ports available
        cmbBaud.Items.Add(9600)                  'Populate the cmbBaud Combo box to common baud rates used
        cmbBaud.Items.Add(19200)
        cmbBaud.Items.Add(38400)
        cmbBaud.Items.Add(57600)
        cmbBaud.Items.Add(115200)

        For i = 0 To UBound(myPort)
            cmbPort.Items.Add(myPort(i))
        Next
        cmbPort.Text = cmbPort.Items.Item(0)    'Set cmbPort text to the first COM port detected
        cmbBaud.Text = cmbBaud.Items.Item(0)    'Set cmbBaud text to the first Baud rate on the list

        btnDisconnect.Enabled = False           'Initially Disconnect Button is Disabled
        Control.CheckForIllegalCrossThreadCalls = False

        objWriter.WriteLine(String.Join(vbTab, New String() {"Date", "Time", "P1",  _
                            "P2", "P1SP", "P2SP", "GV", "Current", "Temp", "B12V", _
                            "B24V", "CVFB1", "CVFB2", "CV_CMD1", "CV_CMD2", "FlowVol", _
                            "FlowLPM", "FlowLPH"}))

        lblPressure1Max.Text = 0
        lblPressure2Max.Text = 0
        lblGeneratorVMax.Text = 0
        lblFlowlpmMax.Text = 0
    End Sub

    '~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
    '   Buttons
    '
    '~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Private Sub btnConnect_Click(ByVal sender As System.Object, ByVal e As System.EventArgs)
        SerialPort1.PortName = cmbPort.Text         'Set SerialPort1 to the selected COM port at startup
        SerialPort1.BaudRate = cmbBaud.Text         'Set Baud rate to the selected value on

        'Other Serial Port Property
        SerialPort1.Parity = IO.Ports.Parity.None
        SerialPort1.StopBits = IO.Ports.StopBits.One
        SerialPort1.DataBits = 8            'Open our serial port
        SerialPort1.Open()

        btnConnect.Enabled = False          'Disable Connect button
        btnDisconnect.Enabled = True        'and Enable Disconnect button

    End Sub

    Private Sub btnConnect_Click_1(ByVal sender As System.Object, _
                            ByVal e As System.EventArgs) Handles btnConnect.Click
        SerialPort1.PortName = cmbPort.Text         'Set SerialPort1 to the selected COM port at startup
        SerialPort1.BaudRate = cmbBaud.Text         'Set Baud rate to the selected value on

        'Other Serial Port Property
        SerialPort1.Parity = IO.Ports.Parity.None
        SerialPort1.StopBits = IO.Ports.StopBits.One
```

```
        SerialPort1.DataBits = 8            'Open our serial port
        SerialPort1.Open()

        btnConnect.Enabled = False          'Disable Connect button
        btnDisconnect.Enabled = True        'and Enable Disconnect button


    End Sub

    Private Sub btnDisconnect_Click(ByVal sender As System.Object, ByVal e As System.EventArgs)
        SerialPort1.Close()             'Close our Serial Port

        btnConnect.Enabled = True
        btnDisconnect.Enabled = False
    End Sub

    Private Sub btnSend_Click(ByVal sender As System.Object, ByVal e As System.EventArgs)
        SerialPort1.Write(txtTransmit.Text & vbCr)         'The text contained in the txtText will
                                                           'be sent to the serial port as ascii
                                                'plus the carriage return (Enter Key) the carriage
                                                'return can be ommitted if the other end does not need it
    End Sub

    Private Sub cmbPort_SelectedIndexChanged(ByVal sender As System.Object, ByVal e As System.EventArgs)
        If SerialPort1.IsOpen = False Then
            SerialPort1.PortName = cmbPort.Text         'pop a message box to user if he is changing ports
        Else                                            'without disconnecting first.
            MsgBox("Valid only if port is Closed", vbCritical)
        End If
    End Sub

    Private Sub cmbBaud_SelectedIndexChanged(ByVal sender As System.Object, ByVal e As System.EventArgs)
        If SerialPort1.IsOpen = False Then
            SerialPort1.BaudRate = cmbBaud.Text            'pop a message box to user
                                                           'if he is changing baud rate
        Else                                               'without disconnecting first.
            MsgBox("Valid only if port is Closed", vbCritical)
        End If
    End Sub

'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'   Serial Port Control
'
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~   Private Sub
SerialPort1_DataReceived(ByVal sender As Object, ByVal e As System.IO.Ports.SerialDataReceivedEventArgs) _
                                    Handles SerialPort1.DataReceived
        'ReceivedText(SerialPort1.ReadExisting())
          'Automatically called every time a data is received at the serialPort

        InputDataSet = SerialPort1.ReadLine() ' LF (Line feed, '\n', 0x0A, 10 dec)
                                              'or CR (Carriage return, '\r', 0x0D, 13 dec)
                                              'individually, or (CR+LF, '\r\n', 0x0D0A) <-- For non-Unix

        If InputDataSet.StartsWith("P") Then
            ' Ignore the bad packet
            ReceivedText(SerialPort1.ReadLine())
            GoodPacket += 1
        Else
            'Nothing
            BadPacket += 1
        End If
        'SerialPort1.ReadChar()
        Application.DoEvents()
```

```
End Sub

Private Sub ReceivedText(ByVal [text] As String)
    'compares the ID of the creating Thread to the ID of the calling Thread

    If Me.rtbReceived.InvokeRequired Then
        Dim x As New SetTextCallback(AddressOf ReceivedText)
        Me.Invoke(x, New Object() {(text)})
    Else
        Me.rtbReceived.Text &= [text]
    End If

      ' P1=0 P2=-45.00 GV=0.00 Cur=5.00 T=0.00 B12V=0.00
      'B24V=0.00 CVFB1=0.00 CVFB2=5.00 CV_CMD1=255 CV_CMD2=100 Flow=0.057 0.000 0.000<\r><\n>
    Dim TestArray1() As String = text.Split(" ")

    If TestArray1.Length = 17 Then
        Data1.Pressure1 = Convert.ToSingle(TestArray1(0).Substring( TestArray1(0).IndexOf("=") + 1))
        Data1.Pressure2 = Convert.ToSingle(TestArray1(1).Substring( TestArray1(1).IndexOf("=") + 1))
        Data1.Pressure1SP = Convert.ToSingle(TestArray1(2).Substring( TestArray1(2).IndexOf("=") + 1))
        Data1.Pressure2SP = Convert.ToSingle(TestArray1(3).Substring(TestArray1(3).IndexOf("=") + 1))
        Data1.Voltage = Convert.ToSingle(TestArray1(4).Substring(TestArray1(4).IndexOf("=") + 1))
        Data1.Current = Convert.ToSingle(TestArray1(5).Substring(TestArray1(5).IndexOf("=") + 1))
        Data1.Temperature = Convert.ToSingle(TestArray1(6).Substring(TestArray1(6).IndexOf("=") + 1))
        Data1.Bat12V = Convert.ToSingle(TestArray1(7).Substring(TestArray1(7).IndexOf("=") + 1))
        Data1.Bat24V = Convert.ToSingle(TestArray1(8).Substring(TestArray1(8).IndexOf("=") + 1))
        Data1.CVFB1 = Convert.ToSingle(TestArray1(9).Substring(TestArray1(9).IndexOf("=") + 1))
        Data1.CVFB2 = Convert.ToSingle(TestArray1(10).Substring(TestArray1(10).IndexOf("=") + 1))
        Data1.CVCmd1 = Convert.ToSingle(TestArray1(11).Substring(TestArray1(11).IndexOf("=") + 1))
        Data1.CVCmd2 = Convert.ToSingle(TestArray1(12).Substring(TestArray1(12).IndexOf("=") + 1))
        Data1.Flow_Total = Convert.ToSingle(TestArray1(13).Substring(TestArray1(13).IndexOf("=") + 1))
        Data1.Flow_LPM = Convert.ToSingle(TestArray1(14).Substring(TestArray1(14).IndexOf("=") + 1))
        Data1.Flow_LPH = Convert.ToSingle(TestArray1(15).Substring(TestArray1(15).IndexOf("=") + 1))
        Data1.OpMode = Convert.ToSingle(TestArray1(16).Substring(TestArray1(16).IndexOf("=") + 1))


        ' Write Text to the given file
        Dim TextForFile = String.Join(vbTab, New String() {Data1.Pressure1, Data1.Pressure2, _
                Data1.Pressure1SP, Data1.Pressure2SP, Data1.Voltage, Data1.Current, Data1.Temperature, _
                Data1.Bat12V, Data1.Bat24V, Data1.CVFB1, Data1.CVFB2, Data1.CVCmd1, Data1.CVCmd2, _
                Data1.Flow_Total, Data1.Flow_LPM, Data1.Flow_LPH, Data1.OpMode})

        objWriter.WriteLine(tDate.ToString("yyyy-MM-dd") & vbTab & Format(TimeOfDay, "HH:mm:ss") _
                & vbTab & TextForFile)
        lblDate.Text = Format(TimeOfDay, "HH:mm:ss")

        ' update numbers on the screen
        '
        lblPressure1.Text = Data1.Pressure1
        lblPressure2.Text = Data1.Pressure2
        lblPres1SP.Text = Data1.Pressure1SP
        lblPres2SP.Text = Data1.Pressure2SP

        'Me.Text = Data1.Pressure1SP
        lblVoltage.Text = Data1.Voltage
        lblCurrent.Text = Data1.Current
        lblTemperature.Text = Data1.Temperature
        lblB12V.Text = Data1.Bat12V
        lbl24V.Text = Data1.Bat24V
        lblCVFB1.Text = Data1.CVFB1
        lblCVFB2.Text = Data1.CVFB2
        lblCVCmd1.Text = Data1.CVCmd1
        lblCVCmd2.Text = Data1.CVCmd2
        lblFlowT.Text = Data1.Flow_Total
        lblFlowLPM.Text = Data1.Flow_LPM
```

```
            lblFlowLPH.Text = Data1.Flow_LPH
            lblOpMode.Text = Data1.OpMode

            'txtPressure1SP.Text = Data1.Pressure1SP
            'txtPressure2SP.Text = Data1.Pressure2SP
            'txtCV1_Cmd.Text = Data1.CVCmd1
            'txtCV2_cmd.Text = Data1.CVCmd2
            'txtOpmode.Text = Data1.OpMode

            lblGoodPackets.Text = GoodPacket
            lblBadPackets.Text = BadPacket

            If Data1.Pressure1 > (lblPressure1Max.Text) Then
                lblPressure1Max.Text = Data1.Pressure1
            End If


            If Data1.Pressure2 > (lblPressure2Max.Text) Then
                lblPressure2Max.Text = Data1.Pressure2
            End If

            If Data1.Voltage > (lblGeneratorVMax.Text) Then
                lblGeneratorVMax.Text = Data1.Voltage
            End If

            If Data1.Flow_LPM > (lblFlowlpmMax.Text) Then
                lblFlowlpmMax.Text = Data1.Flow_LPM
            End If

        End If

        'lblPressure1Max.Text = 0
        'lblPressure2Max.Text = 0
        'lblGeneratorVMax.Text = 0
        'lblFlowlpmMax.Text = 0

    End Sub

    Private Sub BtnContrlCommand_Click_1(ByVal sender As System.Object, ByVal e As System.EventArgs) _
                                         Handles BtnContrlCommand.Click
        SerialPort1.Write(txtPressure1SP.Text & " " & txtPressure2SP.Text _
                    & " " & txtCV1_Cmd.Text & " " & txtCV2_cmd.Text & " " & txtOpmode.Text & vbCr)
    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) _
                                         Handles Button1.Click
        objWriter.Close()

    End Sub
End Class
```

Appendix 3: Patents for Flap-type WEC

Titles for the patents for Flap-type WEC are presented as following:

United States Patent [19]

Smith

[11] **4,170,738**

[45] **Oct. 9, 1979**

[54] **ENERGY DEVICE POWERED BY THE MOTION OF WATER BENEATH WAVES**

[75] Inventor: **E. Quimby Smith**, Camarillo, Calif.

[73] Assignee: **Q Corporation**, Camarillo, Calif.

[21] Appl. No.: **861,967**

[22] Filed: **Dec. 19, 1977**

[51] **Int. Cl.**[2] **F03B 13/12**

[52] **U.S. Cl.** **290/42**; 290/53; 60/398; 185/30; 417/330; 405/195

[58] **Field of Search** 60/327, 398, 499, 504, 60/506, 507; 61/20; 185/29, 30; 290/42, 43, 53, 54; 415/2, 8; 417/100, 330, 332, 333, 334; 405/195

[56] **References Cited**

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850,492	4/1907	Reynolds et al.	417/330
970,048	9/1910	Harmon	417/332 X
3,928,967	12/1975	Salter	60/398
4,002,416	1/1977	Axford	60/398

FOREIGN PATENT DOCUMENTS

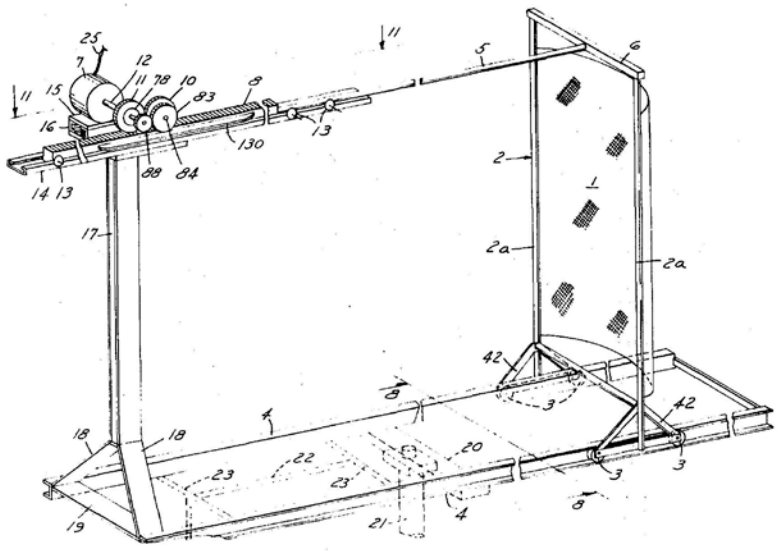
943960	10/1948	France	417/100
1482085	8/1977	United Kingdom	60/398

Primary Examiner—Edgar W. Geoghegan
Attorney, Agent, or Firm—Whittemore, Hulbert & Belknap

[57] **ABSTRACT**

A device for extracting both kinetic and potential energy from the motion of the water beneath waves over a considerable depth comprising a member or sail guided to reciprocate with the movement of the water. The sail is connected to and operates a power device such, for example, as an electric generator or a pump. Multiple units can be arranged in "farms" to furnish megawatts of power.

19 Claims, 15 Drawing Figures



United States Patent [19]
Smith, Jr.

[11] **4,371,788**
[45] * **Feb. 1, 1983**

[54] **ENERGY DEVICE POWERED BY THE MOTION OF WATER BENEATH WAVES**

[75] Inventor: ***E. Quimby Smith, Jr.***, Graeagle, Calif.

[73] Assignee: **Q Corporation**, Troy, Mich.

[*] Notice: The portion of the term of this patent subsequent to Oct. 9, 1996, has been disclaimed.

[21] Appl. No.: **163,033**

[22] Filed: **Jun. 26, 1980**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 56,186, Jul. 13, 1979, which is a continuation-in-part of Ser. No. 861,967, Dec. 19, 1977, Pat. No. 4,170,738.

[51] **Int. Cl.**³ **F03B 13/12**
[52] **U.S. Cl.** **290/42**; 60/499; 60/503; 60/507; 290/53
[58] **Field of Search** 290/42, 43, 53, 54; 60/398, 499, 502–507; 415/2, 8, 66; 417/100, 330, 332, 333, 337

[56] **References Cited**

U.S. PATENT DOCUMENTS

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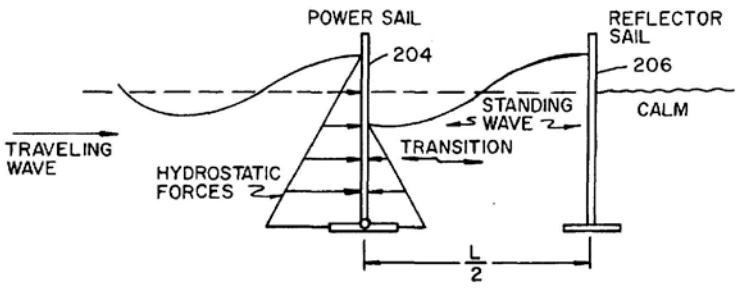
3,965,365	6/1976	Parr	290/53
4,036,563	7/1977	Tornkvist	60/398
4,048,801	9/1977	Tornabene	60/502

Primary Examiner—Ulysses Weldon
Assistant Examiner—Shelley Wade
Attorney, Agent, or Firm—Barnes, Kisselle, Raisch, Choate, Whittemore & Hulbert

[57] **ABSTRACT**

A device for extracting both kinetic and potential energy from the motion beneath waves over a considerable depth comprising a power member or sail guided to reciprocate with the movement of the water. The power sail is connected to and operates a power device such as an electric generator or pump. A second member, or sail, is located in geometric position relative to the power sail to reflect energy back to the power sail. Sensors, servo systems, and computers may be used to optimize power output. Multiple units can be arranged in "farms" to furnish megawatts of power.

29 Claims, 23 Drawing Figures



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International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : **F03B 13/18, F04B 17/00**	**A1**	**(11) International Publication Number:** **WO 98/17911** **(43) International Publication Date:** 30 April 1998 (30.04.98)

(21) International Application Number: PCT/IT97/00258

(22) International Filing Date: 21 October 1997 (21.10.97)

(30) Priority Data:
RM96A000708 21 October 1996 (21.10.96) IT

(71)(72) Applicant and Inventor: LOMBARDO, Mario [IT/IT]; Via Plebiscito, 91, I–95100 Misterbianco (IT).

(74) Agent: MASCIOLI, Alessandro; Via Urbana, 20, I–00184 Roma (IT).

(81) Designated States: JP, US, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
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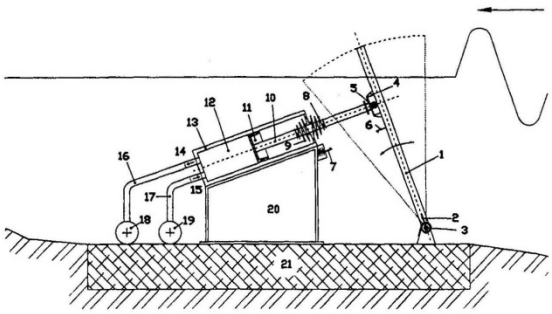
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: WAVE ENERGY GENERATOR INCLUDING AN OSCILLATING GATE AND A PISTON PUMP



(57) Abstract

The electric marine generator with an oscillating sluice–valve and a piston pump allows to exploit the waves' energy for the production of electric energy, the pumping of the water, the compression of refrigerating gases, and comprises: an oscillating sluice–valve (1) with a plane rectangular surface vertically arranged in front of the waves, provided at its base with a hinge (3) fastened to a reinforced concrete block (21), and with a helical spring (2) that allows the return of the sluice–valve when waiting for the wave; a pump (12) consisting of a cylinder (13) and of a piston (11) with a rod (10), having at one end a sliding hinge (5) inserted inside a guide (4) on the sluice–valve (1), provided with two springs (8, 9) for preventing the blows; in the bottom of the cylinder, the sending pipes (16) and the suction pipes (17) are connected, intercepted by the respective one–way safety valves (14, 15); two collectors – a sending collector (18) and a suction collector (19) – which, when connected with pipes (16, 17), allow the formation of pumping systems consisting of a plurality of pumps and respective sluice–valves and arranged in parallel for multiplying the effects; an airlock (CA) is connected to the sending collector for adjusting the motion of the water in the pipes.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
1 May 2003 (01.05.2003)

PCT

(10) International Publication Number
WO 03/036081 A1

(51) International Patent Classification[7]: F03B 13/18

(21) International Application Number: PCT/FI02/00834

(22) International Filing Date: 25 October 2002 (25.10.2002)

(25) Filing Language: Finnish

(26) Publication Language: English

(30) Priority Data:
20012086 26 October 2001 (26.10.2001) FI

(71) Applicant *(for all designated States except US)*: **AW-POWER OY** [FI/FI]; Virtauslaboratorio, c/o FLS Oy, Viikintie 3, FIN-00560 Helsinki (FI).

(72) Inventor; and

(75) Inventor/Applicant *(for US only)*: **KOIVUSAARI, Rauno** [FI/FI]; Kummihovi B 10, FIN-02400 KANTVIK (FI).

(74) Agent: **BERGGREN OY AB**; P. O. Box 16, FIN-00101 HELSINKI (FI).

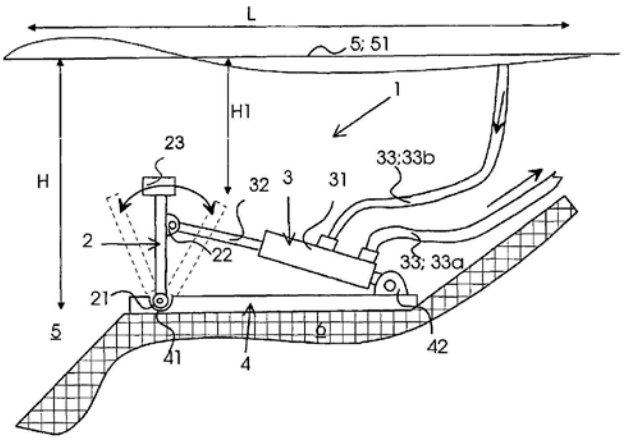
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: A PROCESS AND AN APPARATUS FOR UTILISING WAVE ENERGY



(57) Abstract: The invention relates to a method for utilising wave energy. In the method, the reciprocating movement of a water mass (5) in the vicinity of the bottom (6) of a water basin is adapted to actuate a body (2) or its part attached to the bottom of the water basin, the kinetic energy of the body (2) or its part being recovered into an energy reserve (3), and the energy being transferred from the energy reserve to the object of application. The invention also relates to the apparatus (1) used in the method.

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(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(51) International Patent Classification[7]: F03B 13/18 // 13/14

(21) International Application Number:
PCT/FI2004/000240

(22) International Filing Date: 20 April 2004 (20.04.2004)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
20030635 25 April 2003 (25.04.2003) FI

(71) Applicant *(for all designated States except US)*: **AW-ENERGY OY** [FI/FI]; Sotarovastintie 2, FIN-00370 Helsinki (FI).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **KOIVUSAARI, Bruno** [FI/FI]; Kumminhovi B 10, FIN-02460 Kantvik (FI). **TUOKKOLA, Yrjö** [FI/FI]; Viikintie 3 B 38, FIN-00560 Helsinki (FI). **JÄRVINEN, Arvo** (heiress of the deceased inventor) [FI/FI]; Koivumäentie 13 F 2, FIN-01230 Vantaa (FI). **LILJELUND, John** [FI/FI]; Sammalkalliontie 6 F 128, FIN-02210 Espoo (FI). **HÖYDEN, Antti** [FI/FI]; Korkeavuorenkatu 2 a B 19, FIN-00140 Helsinki (FI). **LAINEMA, Matti** [FI/FI]; Sotarovastintie 2, FIN-00370 Helsinki (FI).

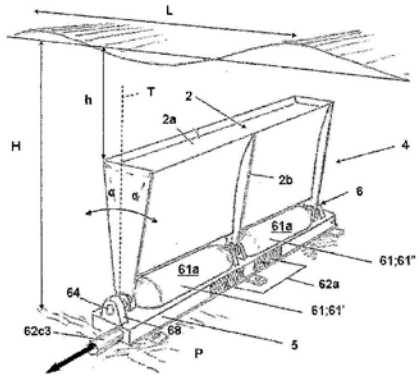
(74) Common Representative: **JÄRVINEN, Arvo**; Koivumäentie 13 F 2, FIN-01230 Vantaa (FI).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PL, PT, RO, SE, SI, SK,

[Continued on next page]

(54) Title: PRODUCTION INSTALLATION



(57) Abstract: A production installation (1) for utilizing wave energy in which production installation there are two or more production units (4) and the water mass (V) of the water basin is adapted to actuate production units (4) or their parts located at the bottom (P) of the water basin or in close vicinity, and the production units (4) can be used to transform the kinetic energy of the water mass into some other form of energy like electric energy and/or kinetic energy and/or pressure of the intermediate agent. The production units (4) are attached directly or indirectly to the bottom of the water basin at intermediate water region (B). The production units (4) are totally submerged under water surface. The transfer equipment of the energy of the production units (4) or of the intermediate substance is connected in series or parallel in relation to each other.

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(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(10) International Publication Number
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(51) International Patent Classification:
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(21) International Application Number:
PCT/GB2006/000906

(22) International Filing Date: 15 March 2006 (15.03.2006)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
0505906.8 23 March 2005 (23.03.2005) GB

(71) Applicant *(for all designated States except US)*: **AQUAMARINE POWER LIMITED** [GB/GB]; Barony House, Stoneyfield Business Park, Inverness IV2 7PA (GB).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **THOMSON, Allan, Robert** [GB/GB]; Wester Aultlugie, Daviot Muir, Inverness IV1 2ER (GB). **WHITTAKER, Trevor, John** [GB/GB]; 8 Cuttles Ridge, Comber, Northern Ireland BT23 SYT (GB). **CROWLEY, Michael, David** [GB/GB]; 11 Glebe Close, Frampton on Severn, Gloucestershire GL2 7E2 (GB).

(74) Agents: **NAISMITH, Robert, Stewart** et al.; Marks & Clerk, 19 Royal Exchange Square, Glasgow G1 3AE (GB).

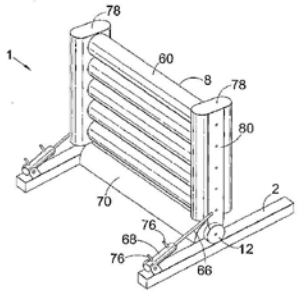
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: APPARATUS AND CONTROL SYSTEM FOR GENERATING POWER FROM WAVE ENERGY



(57) Abstract: The present invention relates to a wave energy conversion device (1) , for use in relatively shallow water, which has a base portion (2) for anchoring to the bed of a body of water (6) and an upstanding flap portion (8) pivotally connected (12) to the base portion. The flap portion is biased to the vertical and oscillates, backwards and forwards about the vertical in response to wave motion acting on its faces. Power extraction means extract energy from the movement of the flap portion. When the base portion (2) is anchored to the bed of a body of water (6) with the flap portion (8) facing the wave motion, the base portion (2) and the flap portion (8) extend vertically through at least the entire depth of the water, to present a substantially continuous surface to the wave motion throughout the full depth of water from the wave crest to the sea bed. A plurality of devices can be interconnected to form one system. The distance between the plurality of flaps is dependent on the wavelenght.

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(12) **United States Patent**
Kobashikawa et al.

(10) **Patent No.: US 7,023,104 B2**
(45) **Date of Patent: Apr. 4, 2006**

(54) **WAVE ENERGY CONVERSION DEVICE FOR DESALINATION, ETC**

(76) Inventors: **Alvin Kobashikawa**, 99-421 Poaha Pl., Aiea, HI (US) 96701; **Yu-Si Fok**, 3185 Oahu Ave., Honolulu, HI (US) 96822

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 32 days.

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(22) Filed: **Jul. 9, 2003**

(65) **Prior Publication Data**

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F04B 35/00 (2006.01)
B01D 61/00 (2006.01)

(52) **U.S. Cl.** **290/42**; 290/53; 417/330; 417/334; 60/398; 416/6; 416/9

(58) **Field of Classification Search** 290/42, 290/53; 417/330, 334; 60/398; 416/6, 9
See application file for complete search history.

(56) **References Cited**

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Primary Examiner—Darren Schuberg
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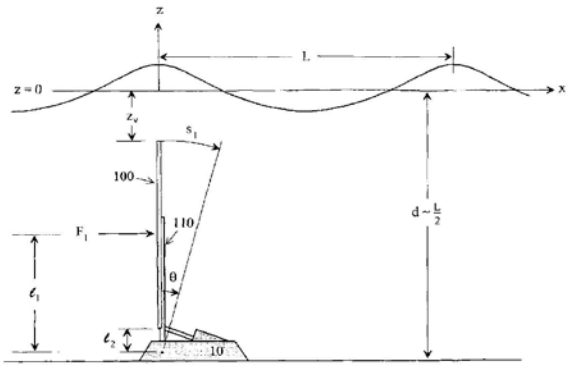
(74) *Attorney, Agent, or Firm*—Leighton K. Chong

(57) **ABSTRACT**

An impulse-type "wave motor" employs a seabed-mounted or supported structure mounting a wave energy absorbing panel on a hinged lever arm for reciprocation motion to obtain optimal absorption of wave energy from wave motion in the sea. For deepwater wavelengths of L, the panel is optimally positioned in a region within L/2 depth from the sea surface. The panel motion is coupled by a connecting rod to a fluid pump which generates a high-pressure fluid output that may be used to drive a reverse osmosis desalination unit or to produce other useful work. Seawater or brackish water may be desalinated through reverse osmosis membranes to produce water quality for consumption, agricultural, or other uses. The submerged operating environment of the device in a region of one-half the design wavelength provides the maximum available energy flux and forced oscillations. The pump may be of the positive-displacement piston type, plunger type, or multi-staging driver type, or a variable volume pump.

20 Claims, 7 Drawing Sheets



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(75) Inventors/Applicants *(for US only)*: **JÄRVINEN, Arvo** [FI/FI]; Koivumäentie 13 F 2, FI-01230 Vantaa (FI). **TUOKKOLA, Yrjö** [FI/FI]; Myllypellonpolku 3 A 4, FI-00650 Helsinki (FI). **KÄHÖNEN, Raimo** [FI/FI]; Hyppyritie 11, FI-11120 Riihimäki (FI).

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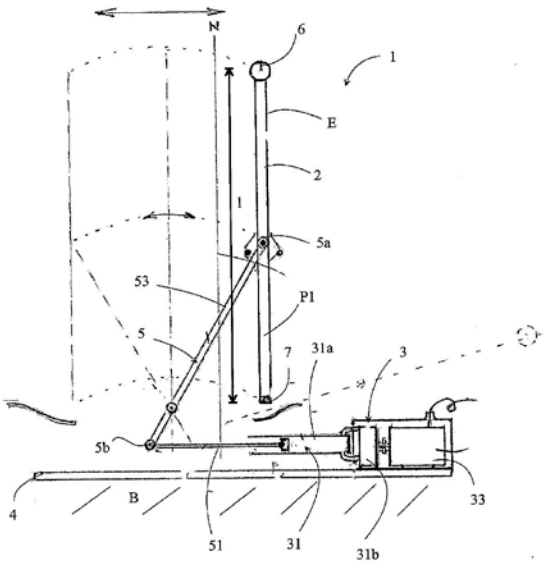
(54) **Title:** APPARATUS FOR RECOVERING WAVE ENERGY



(57) **Abstract:** The invention relates to an apparatus for the recovery of wave energy (1) fastened at the bottom of a water basin, comprising a primary wave energy recovery unit (3), a part moving by the action of the water mass motion caused by waves, and a lever system (5) transmitting kinetic energy from the said moving part to the primary energy recovery unit (3). The plate like element (2) moving by the action of the water mass motion is arranged to move so that the main kinetic component is always approximately at the same angle in relation to the surface plane (e) of the plateline element (2).

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(12) **Patent Application Publication**

KOIVUSAARI et al.

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(43) **Pub. Date: Sep. 30, 2010**

(54) **METHOD FOR INSTALLING AND SERVICING AN APPARATUS RECOVERING THE KINETIC ENERGY OF WATER, AND AN APPARATUS RECOVERING THE KINETIC ENERGY OF WATER**

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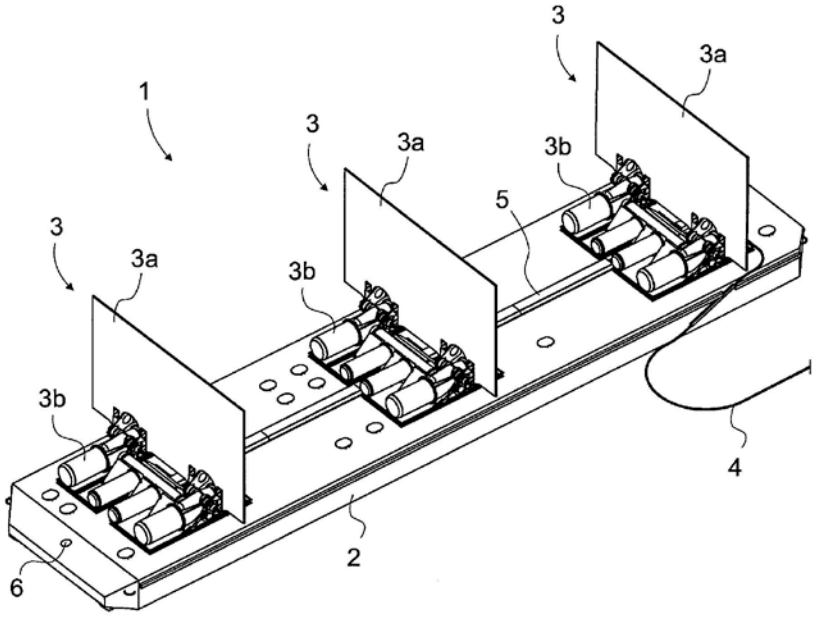
F03B 13/14 (2006.01)

(52) **U.S. Cl.** **114/333**; 290/53

(57) **ABSTRACT**

The object of the invention is a method for installing and servicing an apparatus module (**1**) recovering the kinetic energy of water; and the apparatus module (**1**) itself. The apparatus module (**1**) with wave energy recovering units (**3**) is descended into the sea bottom (**12**) and is kept steady at the sea bottom (**12**) by the help of its own mass and the mass of the water filled into the compartments (**2***a* and **2***c*) in the body (**2**) of the apparatus module (**1**). Correspondingly the apparatus module (**1**) is lifted into the surface of the water and made floating by the help of air that is blown to the compartments (**2***a*) and (**2***c*) in order to replace the water.



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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) **Title**: IMPROVED APPARATUS FOR GENERATING POWER FROM WAVE ENERGY

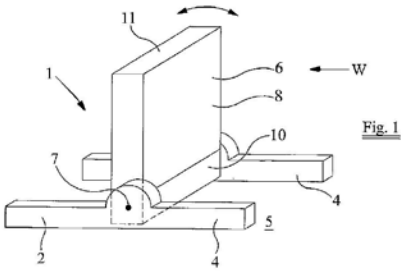

Fig. 1

(57) **Abstract**: A wave energy conversion device (1), for use in relatively shallow water, includes a base portion (2) for anchoring to the bed of a body of water. A flap portion (6) is pivotally connected to the base portion (2) and is biased to the vertical. The flap portion (6) oscillates backwards and forwards about the vertical in response to wave motion. The flap portion (6) includes an upper portion (8) upstanding above the pivot axis (7) for extracting energy from the wave motion and a lower portion (10) that has a biasing mass located below the pivot axis. The biasing mass provides a restoring force acting to bias the flap to the vertical when the flap portion (6) oscillates. Power extraction means is provided for extracting energy from the movement of the flap portion.

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